APPLICATION OF OPTIMIZATION TO THE PRODUCTION PLANNING OF CONSTRUCTION PREFABRICATION SUPPLY CHAINS

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Abstract

Application of Optimization to the Production Planning of Construction Prefabrication Supply Chains

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Prefabrication and modularization are a growing trend in the construction industry. Efficiencies of the operation of construction prefabrication and modularization (CP&M) supply chains result in benefits for construction projects. Although the variable delivery time of construction schedules impacts the operation efficiencies of CP&M supply chains, few studies have investigated this problem by addressing uncertainties in CP&M schedules. On the other hand, the growing interest in CP&M motivates many prefabrication companies to open multiple fabrication shops and allocate jobs between these shops based on various factors. Nonetheless, few quantitative models are available to facilitate this allocation, and research on the CP&M supply chain with multiple shops is scarce. This study aims to fill this gap by investigating the application of optimization to facilitate the production planning of the CP&M supply chain with multiple fabrication shops. This study starts with a literature review covering 110 CP&M papers to understand common improvement strategies. Seven strategies were identified including using building information modelling, focusing on product design, using advanced technologies, applying lean principles, utilizing optimizations in production planning, utilizing optimizations in design and using simulation. Then, an industry survey with 10 fabricators is performed to understand current practices and impacts of uncertainty. After that, two optimization models for job allocations and production planning are developed: one is a deterministic model and the other is a stochastic programing model with multi objectives. Each optimization model is demonstrated through an example problem. The first model generates an optimal solution for the example problem that saves 2.5% of total cost compared to the Early Due Date method. The second model allows to develop a robust set of optimal schedules subject to uncertainty and flexible in balancing cost and time reduction objectives. Its example shows that variable delivery time causes up to 2.93% of total cost increase. Moreover, a sensitivity analysis is introduced to quantify impacts of parameters sensitive to supply chain performance and identify improvement opportunities. This research is expected to contribute the knowledge on production planning of CP&M supply chain under uncertainty and enhance CP&M supply chain performance, therefore benefit construction projects and the construction industry.

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I would like to also thank my advisor, Prof. Zelda B. Zabinsky. Operations research with optimization is beyond my background in construction management. Her profound knowledge in operations research has helped me achieve basic knowledge about this field and gain confidence in solving optimization problems related to my doctoral research. Her support, guidance and critical review has also helped me greatly in writing and completing this dissertation. It has been an utmost pleasure to work with her and have her on my doctoral committee.

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DEDICATION

To my parents, Quang Ho and Hue Nguyen, and to my daughters, Linh Le and Thu Le, who show me the meanings of life and always stay by my side to support

Chapter 1. INTRODUCTION

Construction prefabrication and modularization (CP&M) is the practice of making construction components or assemblies off-site and then delivering the components or assemblies to construction sites for installation. By making construction components in advance and shifting the works off-site, prefabrication and modularization can exploit advanced technologies and operation methods of the manufacturing sector to improve productivity, enhance quality, reduce waste and speed up schedule. These benefits make prefabrication and modularization a growing trend in the construction industry. A study carried out by Mc-Graw Hill Construction (2013) revealed that nearly all construction stakeholders expect to utilize prefabrication in some of their projects. The number of research papers relating to CP&M has also increased significantly in recent years, indicating a growing scholarly interest in the subject.

The literature about CP&M comprises of a wide range of studies, from evaluating the applicability of construction prefabrication (Azhaz, 2013; Chen et al., 2010a &b; Legmpelos, 2013; Murtaza et al., 1993), investigating the best practices (O'Connor et al., 2014; Said, 2015), identifying benefits and challenges (Alvarez-Anton et al., 2016; Dave et al., 2017; Mao et al., 2016; Shahzard, 2016) to investigating the design, fabrication, transportation and installation processes (Isaac et al., 2016; Jensen et al., 2009; Kim et al., 2013; Solnosky et al., 2014). As a result, a comprehensive literature review in CP&M is needed to investigate the current state-of-the-art research in this field and identify further research needs and opportunities. Although many literature review papers have addressed different areas in the construction sector, such as the literature review about the application of radio frequency identification technology (Valero et al, 2015), the partnering relationship in construction (Bygball et al., 2010), and the forms of corruptions in the construction industry (Chan & Owusu, 2017), few papers focused on construction prefabrication and modularization. Li et al. (2014) collected 100 published papers regarding construction prefabrication in 10 leading journals in the period 2000-2013. The study identified the five categories of major research interests in this field including: industry prospect; development and application; evaluation on performance; technology application environment;

and methods for design, production, transportation and assembly. However, no literature review has identified and categorized different improvement strategies for this supply chain. Since prefabrication and modularization are applied widely in the construction, the efficiency of CP&M supply chain results in the benefit for the construction industry. Therefore, identifying the improvement strategies for the operation of this supply chain helps construction researchers and practitioners enhance this supply chain and investigate future improvement opportunities. Responding to this need, this study incorporates an an extensive literature review covering a wide range of CP&M papers that focused on improvement strategies. The papers were classified based on years of publication, country of authors, project types, types of construction materials and systems, and suggested improvement strategies. This study also summarizes the benefits and challenges of CP&M as discussed in the literature. Chapter 3 discusses the methods and results of the literature review.

The growing interest in CP&M also motivates many fabrication companies to open multiple fabrication shops in different areas to meet customer demands and to reduce cost. Jobs and inventory are allocated between these shops based on various factors such as transportation distances and shop capacities. During a preliminary survey carried out with six construction fabricators in the Pacific Northwest in 2017, I found that two of the fabricators participated in the survey are operating multiple fabrication shops and allocating jobs between these shops. However, few comprehensive quantitative models are available to help construction fabricators quantify the outcome of different allocation options and facilitate their decision-making processes. Allocation decisions are made based only on an approximate trade-off between factors such as available capacities, job requirements and transportation distance. The lack of quantitative models makes managers lose the opportunity to select the best possible solutions, thus causing the risk of wasting resources and squandering capacities. This poses an urgent need to develop an approach that supports construction prefabrication managers in allocating jobs and inventory. The current research responds to this need by developing an optimization model for the planning and scheduling of the CP&M supply chains with multiple fabrication shops. Chapter 5 presents the development of this optimization model, followed by an example problem and computational results.

While enhancing the operations of CP&M supply chains results in benefits for the construction industry, the uncertainty of construction projects significantly impacts the operations of prefabrication supply chain. Despite that, little research has been done to quantify the impact of uncertainty on the production planning of CP&M supply chains. On the other hand, cost and time are two critical factors to consider when planning its production process. Although reducing cost and gaining profit are essential business goals, delivering products in a timely manner is important to maintain the supply chain's credential. Timely delivery is critical since delaying the delivery of prefabricated products could stop the field installations of related works and delay the works of other construction trades. The supply chain managers can achieve substantial benefits if they can evaluate the tradeoffs between time and cost to flexibly schedule production systems to handle time and cost reductions proactively. This research bridges this gap by investigating the impact of uncertainty regarding required delivery times on the production planning of the CP&M supply chains with multiple fabrication shops. In 2018-2019, I carried out another survey with six construction fabricators to study the impact of uncertainty and get further understanding about the production planning of CP&M supply chains. Then I developed a multi-objective stochastic programing model with various scenarios about variable delivery time. This model allows to generate a robust set of production and delivery schedules subject to the changes in required delivery time and flexible in balancing cost and delay reduction objectives. The model is presented in Chapter 6, followed by an example problem and computational results.

Chapter 2. RESEARCH APPROACH

Overview: This chapter presents research questions, research methods and the outline of this dissertation.

2.1 RESEARCH QUESTIONS

The research questions evolved throughout the development of this study. My inquiry started with my need to understand the research state in construction prefabrication and modularization (CP&M) and the strategies to improve CP&M supply chains that have been suggested in previous studies. At the same time, I carried out a preliminary industry survey with CP&M companies to understand industry practices and their needs for improvement. The preliminary survey reveals that many CP&M companies organize multiple fabrication shops and allocate jobs and inventory between these shops, but few quantitative models are available to facilitate the job allocation and production planning of these supply chains. The fact that optimization is commonly used in the other industry sectors to solve job allocation problems made me question if optimization could be used to facilitate the job allocations of the CP&M supply chains with multiple fabrication shops. On the other hand, uncertainty about construction schedule could reduce the efficiency of the operations of CP&M supply chains, causing a need to consider the uncertainty in the production plan of CP&M supply chains and to quantify its impact. This motivated me to carry out another industry survey to understand the impact of uncertainty on the performance of CP&M supply chain. This also prompted me to develop a stochastic programming model for the production planning of CP&M supply chain that considers various scenarios about required delivery times. In general, the main research questions of this doctoral research include:

- Question 1: What are the improvement strategies for CP&M supply chains as suggested in the literature?
- Question 2: How does optimization support the production planning and job allocations of CP&M supply chains with multiple fabrication shops?

- Question 3: How does uncertainty in construction schedules impact the performance of CP&M supply chains and how to consider uncertainty when developing the production plan of CP&M supply chains with multiple fabrication shops?

2.2 RESEARCH METHOD

This research employs an interdisciplinary approach between construction management and industrial engineering. It encompasses construction prefabrication supply chains, construction scheduling, and operations research. This research aims to understand the current state of construction prefabrication supply chain and support the production planning of these supply chains under uncertainty. To achieve these goals and find the answer for above research questions, this study comprises of the following steps:

- Step 1: Perform an extensive literature review about the improvement strategies for CP&M supply chains.
- Step 2: Investigate the current practice used for the production planning of CP&M supply chains, the impact of uncertainty, and the opportunities to adopt optimization into these supply chains.
- Step 3: Develop algorithms for optimization models to support the job allocations and production planning of prefabrication supply chains with multiple fabrication shops.
- Step 4: Create and solve example problems.
- Step 5: Analyze and discuss computational results.

Step 1. Literature Review

This study performed an extensive literature review covering 110 CP&M papers published from 1990 to 2017 in order to understand common strategies proposed in the literature for the improvement of the CP&M supply chains and to identify future research opportunities. To ensure covering the studies available in the literature regarding construction prefabrication, this study targets the search to major research databases in construction, including: Science Direct (sciencedirect.com), ASCE Research Library (ascelibrary.org), IEEE Xplore (ieeexplore.ieee.org). In addition, the search area is extended to Google Scholars (scholar.google.com) to minimize the possibility of missing papers not published in the former databases. “Construction”, “prefabrication” and “modularization” are key words that were used consistently in all databases to search for these papers.

Step 2. Study Industry Practice

To understand the current practices in operating prefabrication supply chain systems, focusing on how to develop prefabrication production planning in responding to the uncertainty of construction schedules, I carried out two industry surveys, each with six construction fabricators in the Pacific Northwest. The first survey was carried out in 2017, and the second one in 2018-2019. The first survey was to understand the current practices and study improvement needs in construction prefabrication and modularization. The second survey was an extension of the first, which focused on the impact of uncertainty on supply chain performance. Based on the survey results, I developed optimization models that aim to assist the production planning of prefabrication supply chains with multiple fabrication shops.

Step 3. Develop Algorithms for Optimization Models

Based on the knowledge generated by the operations research domain, this study develops the algorithms for optimization models to facilitate the production planning of prefabrication supply chain with multiple fabrication shops. I create two optimization models, a deterministic model and a stochastic programing model. The deterministic model is a type of model where the parameters are well known, and no uncertainty is included. The deterministic model is less complicated, easier to develop and can be solved quickly compared to the other models. However, it does not consider uncertainty in the model itself. The stochastic programming (SP) model is a type of optimization model involving uncertainty. SP is suitable when the probability distribution of the variables is unknown, but some historical data is available to predict possible scenarios. However, solving the SP model requires a significant computational time because of many variables created from different scenarios. To study the tradeoffs between cost and time , I also incorporate multi-objectives including cost reduction and delay reduction objectives into the stochastic programming model. The algorithms for the deterministic model are discussed in Chapter 5, and the algorithms for the stochastic programming model are presented in Chapter 6.

Step 4. Prepare and Solve Example Problems

To demonstrate and verify the performance of the optimization models, the I developed two example problems. The first problem is the for the deterministic model with two fabrication shops, three jobs and eight job parts. The second problem is an extension of the first problem and is used for the stochastic programming model. The second problem includes three fabrication shops, ten jobs and fifteen job parts. The first problem is solved using CPLEX optimization software package (CPLEX version 12.7, 2016) and using Microsoft Excel (version 2016) to create input data and write the computation results. To streamline the creation of input data and the analysis of computational results, the second problem is solved using DOCPLEX, an IBM Decision Optimization CPLEX Modeling for Python (DOCPLEX version 2.9.141, 2019). The input data for the optimization model is written in a relational database management system named SQLite (version 3.10.1, 2016). The example problem 1 and the example problem 2 are presented in Chapter 5 and Chapter 6, respectively.

Step 5. Analyze and Discuss Computational Results

The computational results generated from above problems are analyzed to evaluate the performance of the optimization models, study the tradeoffs between cost and time, recognize potential applications of the optimization models and identify improvement opportunities. The outcome and findings of these problems are presented in Chapter 5 and Chapter 6. Chapter 5 is for the deterministic problem and Chapter 6 is for the stochastic programming problem.

2.3 DISSERTATION OUTLINE

This dissertation comprises of the following chapters:

- Chapter 1: Introduction. This chapter provides an overview about research problems and the need to carry out this study.
- Chapter 2: Research approach. This chapter provides information about the research questions, research method and dissertation outline.
- Chapter 2: Literature review. This chapter presents a literature review about improvement strategies for construction prefabrication and modularization.

- Chapter 3: Industry surveys. This chapter introduces two industry surveys carried out in this study with prefabrication companies to understand industry practices and improvement needs.
- Chapter 4: Production planning of the CP&M supply chains with multiple fabrication shops under deterministic conditions. This chapter presents the development of a deterministic optimization model for the job allocations, followed by an example problem and computational results. This chapter is mostly based on a research paper that is under review by the Journal of Construction Engineering and Management (Ho et al. 2019).
- Chapter 5: Production planning of the CP&M supply chain with multiple fabrication shops under uncertainty. This chapter presents the development of a multi-objective stochastic programming model for the job allocations and production planning. The uncertainty is included in the model through various scenarios about required delivery times. An example problem that demonstrates the stochastic programming model and computational results are also presented in this chapter.
- Chapter 6: Conclusion. This chapter summarizes research findings and discusses the directions for future research.

Chapter 3. LITERATURE REVIEW

Overview: Construction prefabrication and modularization is a growing trend indicated through a significant increase in the number of studies relating to this area in recent years. However, there is a shortage of literature reviews addressing improvement strategies for CP&M supply chains. This chapter presents an extensive literature review covering 110 CP&M papers published from 1990 to 2017 in order to understand common strategies proposed in the literature for the improvement of the CP&M supply chains and identify future research opportunities. Seven improvement strategies were identified including using building information modelling, focusing on product design, using advanced technologies, applying lean principles, utilizing optimizations in production planning, utilizing optimizations in design, and using simulation. Most CP&M studies focus on the residential sector and the civil industrial sector. The types of materials/systems addressed mostly were steel structures, wood structures and the mechanical, electrical and plumbing (MEP) system.

3.1 PAPER SELECTION PROCEDURE

To select the studies regarding construction prefabrication and modularization, I used the key words “construction”, “prefabrication” and “modularization” for searching and targeted the search to major academic databases in construction, including: Science Direct (sciencedirect.com), ASCE Research Library (ascelibrary.org), IEEE Xplore (ieeexplore.ieee.org) and Google Scholars (scholar.google.com). This literature review used the searching steps adapted from Lima-Junior and Carpinetti (2017) as follows:

- 1st step: Type the key words into the search databases.
- 2nd step: Limit the searching frame from year 1990 to 2017.
- 3rd step: Select the first 200 results achieved from above steps.
- 4th step: Filter the results by including only papers published in academic journals, master theses and doctoral dissertations.
- 5th step: Filter the results one more time by reviewing these papers to ensure retrieving papers relevant to construction prefabrication and modularization.

- 6th step: Remove duplicate and conference papers whose authors have a journal paper with insignificant changes.
- 7th step: Select and analyze the papers addressing the strategies to improve CP&M supply chain as well as the benefits and challenges of CP&M.

Table 3.1 below presents the quantity of papers achieved through the database search process.

Table 3.1 Literature search range

Source	**Keyword**	**Search result**	**Select the first 200 results**	**Select the papers dealing with construction prefabrication and modularization**	**Eliminate duplications**	**Select the papers addressing benefits, challenges and improvement strategies**
Science direct	Construction prefabrication modularization	490	200	110	170	110
ASCE Research Library		122	122	38		
IEEE Xplore		56	56	8		
Google Scholar		1240	200	107		

3.2 LITERATURE REVIEW FRAMEWORK

To direct the literature study towards my study objectives, I developed a framework indicating the main characters of various papers in CP&M. First, seven groups of factors were identified, including the year of publication, country of author, project types, material/system types, benefits and challenges, and improvement strategies. Second, I carefully reviewed these papers and identified the specific study areas addressed in each paper and assigned them to the respective groups. Last, I counted the total number of papers in each area of study and analyzed research trends. Since each paper may present multiple strategies, the sum of the number of papers of all groups can be different from the total number of papers studied in this literature review. Figure 3.1 presents this literature review framework.

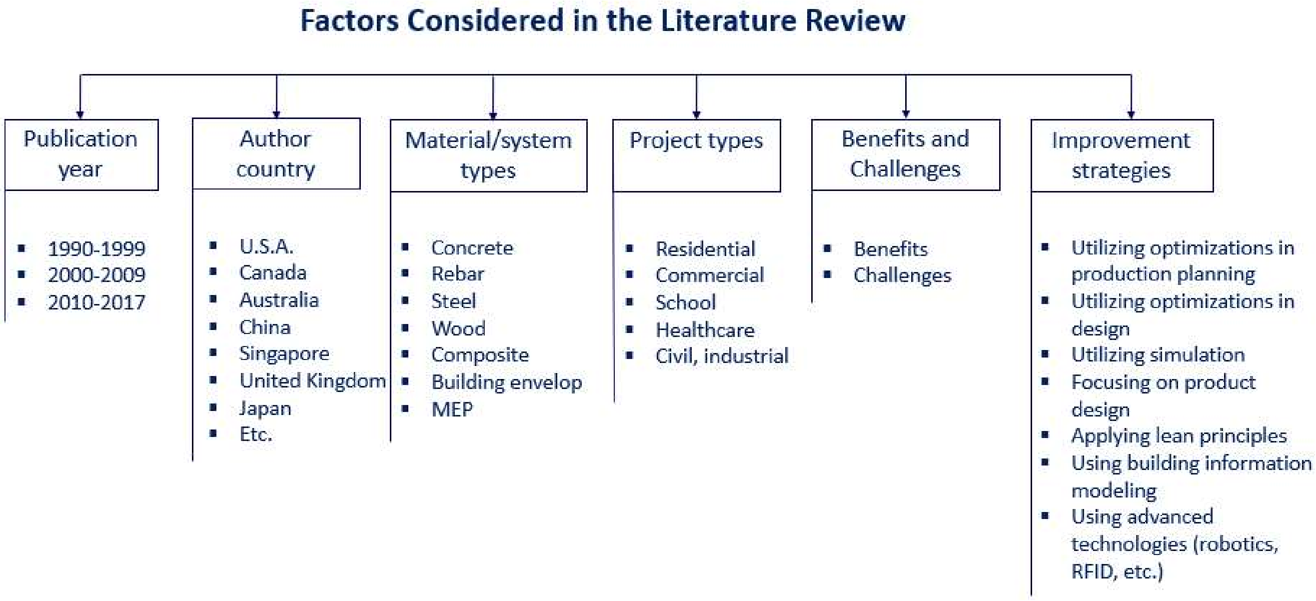


Figure 3.1 Framework for the literature study about improvement strategies for CP&M

The groups of criteria analyzed in this literature review focus on:

- Year of publication: to understand research trends over each time period. The publication dates of the papers are categorized into 10-year periods including 1990-1999, 2000-2009, 2010-2017.
- Authors' country: to reveal the quantity of CP&M studies at different global regions. The country of the authors who published the research papers are recorded such as the U.S., U.K., Canada, China, Malaysia.
- Material/system types: to understand research interests in term of material/system types that are used. The types of construction materials/systems addressed in these studies are identified and grouped into concrete, rebar, steel, wood, composite, building envelop system and MEP system.
- Project types: to understand research interests in term of project types. The project types involved in these research papers are identified and classified into major areas including residential, commercial, school, healthcare, and civil infrastructures.
- Benefits and challenges: to get a clearer understanding about the improvement needs for CP&M. The benefits and challenges are identified and synthesized into a table.

- Improvement strategies: to understand the current practices and to identify future improvement opportunities. Various improvement strategies for the CP&M supply chain are recognized, including using optimization for production planning, using optimization for design, applying simulation, focusing on product design, utilizing lean principles, applying building information modeling and using advanced technology.

The next sections present the main content implicated in the literature based on the above groups of interest and the findings of this literature review.

3.3 CHARACTERIZATION AND DISCUSSION OF RESULTS

Years of Publication and Author Countries

The number of studies about improvement strategies as well as the benefits and challenges of CP&M (construction prefabrication and modularization) increased steadily from 1990 to 2017 as shown in Figure 3.2. This reflects the growing interest in CP&M from academia and suggests a wide application of CP&M in the industry. As shown in Figure 3.3, most of the studies came from the U.S., then China, Canada, Australia and U.K. Other countries such as Malaysia, India, Italy and France also contributed a moderate number of relating papers.

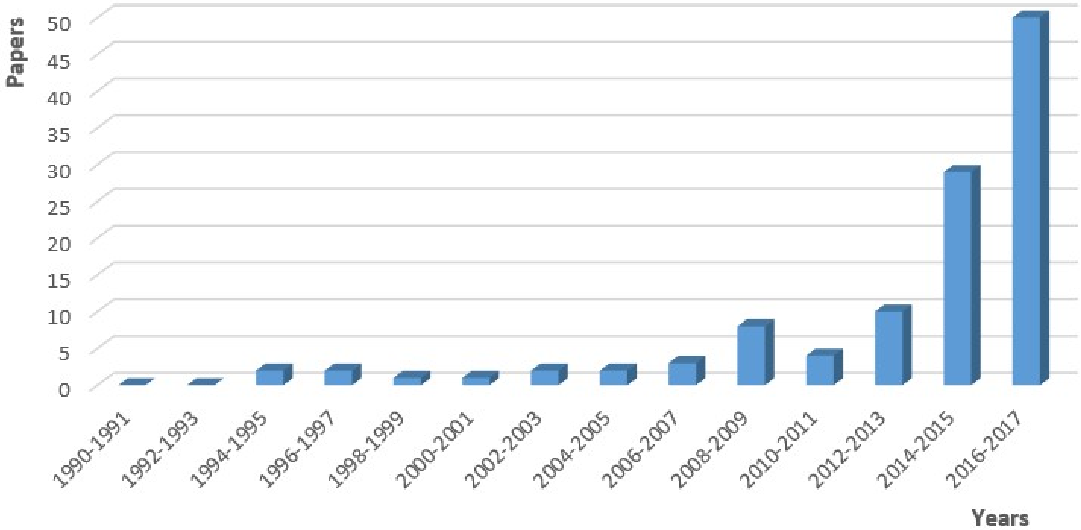


Figure 3.2 Year of publication

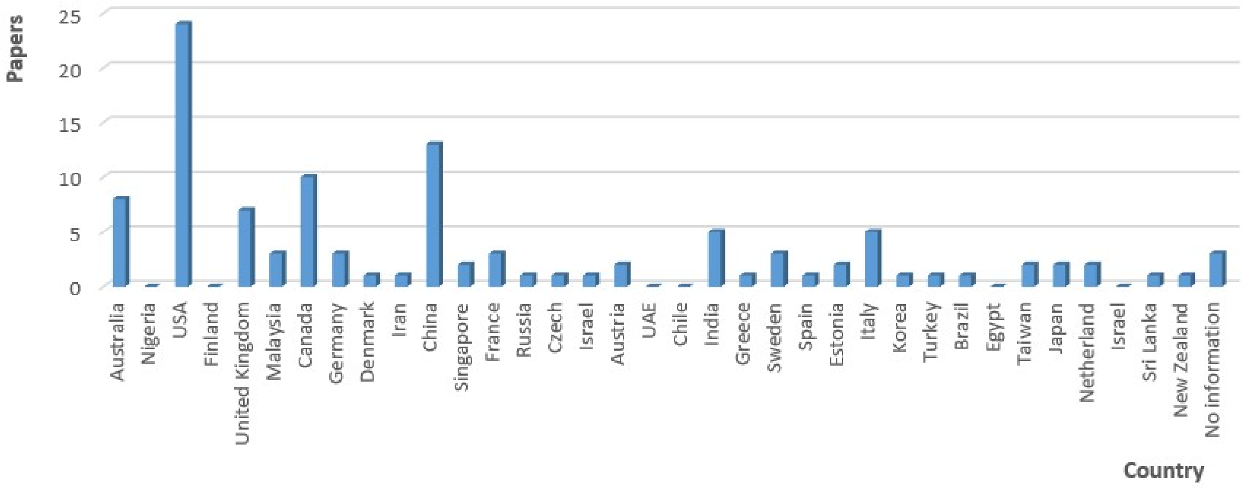


Figure 3.3 Country of authors

Types of Construction Materials and Systems

Types of prefabricated materials/systems addressed in the literature through 1990-1999, 2000-2009, 2010-2017 are shown in Figure 3.4. Concrete, steel and MEP system receive lots of attention from researchers. However, only few studies focused on prefabricated rebar and composite materials. Beside these studies, there are many papers addressing CP&M systems in general without focusing on any particular CP&M systems.

	Concrete	Rebar	Steel	Wood	Composite	Bldg Envelop	MEP
Year 1990-1999	0	0	1	0	0	0	1
Year 2000-2009	2	1	0	1	0	2	1
Year 2010-2017	6	0	10	9	3	4	8

Figure 3.4 Types of prefabricated material/system addressed in the literature

Project Types

Many studies focused on the overall application of CP&M without addressing the type of building sector. When building sectors are addressed, the residential sector receives the most attention and has 27 papers. Following this category is the civil industrial sector with 17 papers as shown in Figure 3.5.

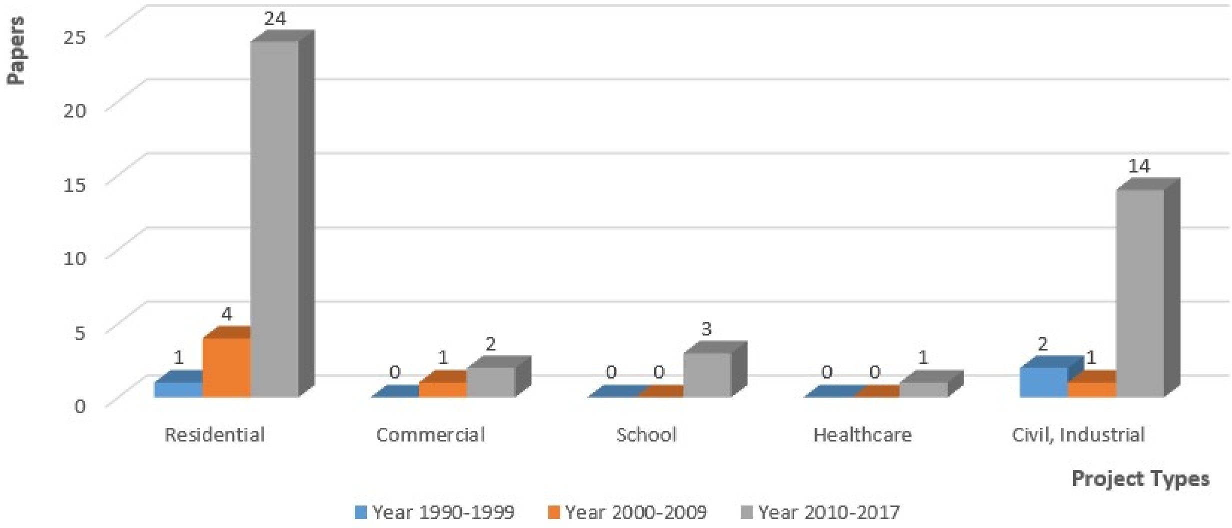


Figure 3.5 Project types

Benefits and Challenges

Benefits and challenges of CP&M are discussed in many papers. The common benefits of CP&M include a reduced cost, enhanced productivity, reduced time, decreased waste, improved safety and enhanced quality. On the other hand, CP&M also contains certain challenges such as reduced design flexibility, difficult demands in transportation and hoisting, market resistance, high upfront cost, limited number of suppliers and lack of skilled workers. Tables 3.2 and 3.3 list out various benefits and challenges of CP&M systems.

Table 3.2 Benefits of construction prefabrication and modularization

Criteria	**Authors**																											
	Alvarez-Anton et al. (2016)	Arditi et al. (2000)	Bertelsen (2005)	Blankinship (2008)	Burke and Miller (1998)	Chaoming et al. (2016)	Dave et al. (2017)	Generalova et al. (2016)	Jiang et al. (2017)	Kamali and Hewage (2016)	Khan and Jain (2017)	Khaleghian et al. (2016)	Koppelhuber et al. (2017)	Li et al. (2016)	Li et al. (2017b)	Mao et al. (2015)	Mao et al. (2016)	Mohammad et al. (2016)	Musa et al. (2014a)	Naqvi et al. (2014)	O'Connor et al. (2015)	Parra and Bono (2015)	Pero et al. (2015)	Shahtaheri et al. (2017)	Shahzard (2016)	Shen et al. (2009)	Stallen et al. (1994)	Tam et al. (2006, 2014)
Reduced cost	x		x	x		x		x	x	x	x									x	x	x	x		x	x	x	
Increased quality			x	x	x	x		x												x								
Fasten schedule									x	x								x		x		x	x		x			
Improved safety				x					x	x										x		x						
Waste reduction	x																	x								x		x
Better working and testing environment																				x	x							
Greater constructability for EPC power project					x																							
Enhanced productivity						x				x	x	x										x			x			
Lower risks					x																							
More durable																			x									
Environmental friendly								x	x	x									x									
Better life quality																												
Less impacted by severe weather conditions																				x		x						
Utilize low skill levels																				x							x	
More opportunities for women																					x						x	
Generate employment																					x						x	
Multiple uses of one design																					x							
Can design and procure in advance																					x							
Can carry out paralleled or accelerated engineering																					x							
Have learning curves from fabrication, commissioning, installation and operation																					x							
Have volume discounts in the procurement																					x							
Some regions have an extensive experience about prefabrication														x														
Some regions pay efforts in promoting information technology in prefabrication														x														
Some regions get the consensus from building authority in promoting prefabrication technology														x														

Table 3.3 Challenges of construction prefabrication and modularization

Criteria	Authors																											
	Alvarez-Anton et al. (2016)	Arditi et al. (2000)	Bertelsen (2005)	Blankinship (2008)	Burke and Miller (1998)	Chaoming et al. (2016)	Dave et al. (2017)	Generalova et al. (2016)	Jiang et al. (2017)	Kamali and Hewage (2016)	Khan and Jain (2017)	Khaleghian et al. (2016)	Koppelhuber et al. (2017)	Li et al. (2016)	Li et al. (2017b)	Mao et al. (2015)	Mao et al. (2016)	Mohammad et al. (2016)	Musa et al. (2014a)	Naqvi et al. (2014)	O'Connor et al. (2015)	Parra and Bono (2015)	Pero et al. (2015)	Shahtaheri et al. (2017)	Shahzard (2016)	Shen et al. (2009)	Stallen et al. (1994)	Tam et al. (2006, 2014)
More effort in project planning										x			x															
Need more effort in coordination and communication										x																		
Restraint in transportation				x						x	x																	
Negative perception and reluctant toward utilizing new construction method										x						x												
High initial cost									x	x						x	x			x	x							
Unavailability of skilled personnel										x			x		x													
Reduce flexibility in design and construction			x																				x					
Require proper design and decision support framework							x																					
Early commitment from design process											x																	
Lack of knowledge and education		x											x															
Inadequate policy and standard									x						x													
Lack of regulations and incentives from government																x												
Sacrificed customization																					x							
Constraint in hoisting				x																								
Market resistance									x																			
Lack of project team coordination									x																			
Limited number of suppliers											x									x								
Unavailability of fittings/valves/sub-components															x													
Additional cost for off-site quality management																				x								
Additional cost and time for transportation and logistics																				x								
Additional cost and time for feasibility study																				x								
Additional cost for hoisting																				x								
Additional cost to upgrade infrastructure for transportation																				x								
Additional cost to assess the market and establish scope																					x							
Some regions lack of information exchanges between the design and prefabrication phases														x														
Some regions lack of the visibility and traceability in real-time information														x														
Some regions have information gaps in stakeholders, technologies and processes														x														

Strategies to Improve Construction Prefabrication/Modularization

Various strategies to improve CP&M supply chains have been suggested in previous studies, from focusing on product design, utilizing building information modeling, applying optimizations and lean principles to using advanced technologies such as automations or robotics. Figure 3.6 shows the main strategies for the improvement of construction prefabrication/modularization as addressed in these studies. This figure indicates that most of the studies focused on product designs (address the design of CP&M products) with 28 papers, and the application of building information modeling with 24 papers. However, only a moderate number of studies pay attention to optimizations in design (5 papers) and in production planning (7 papers).

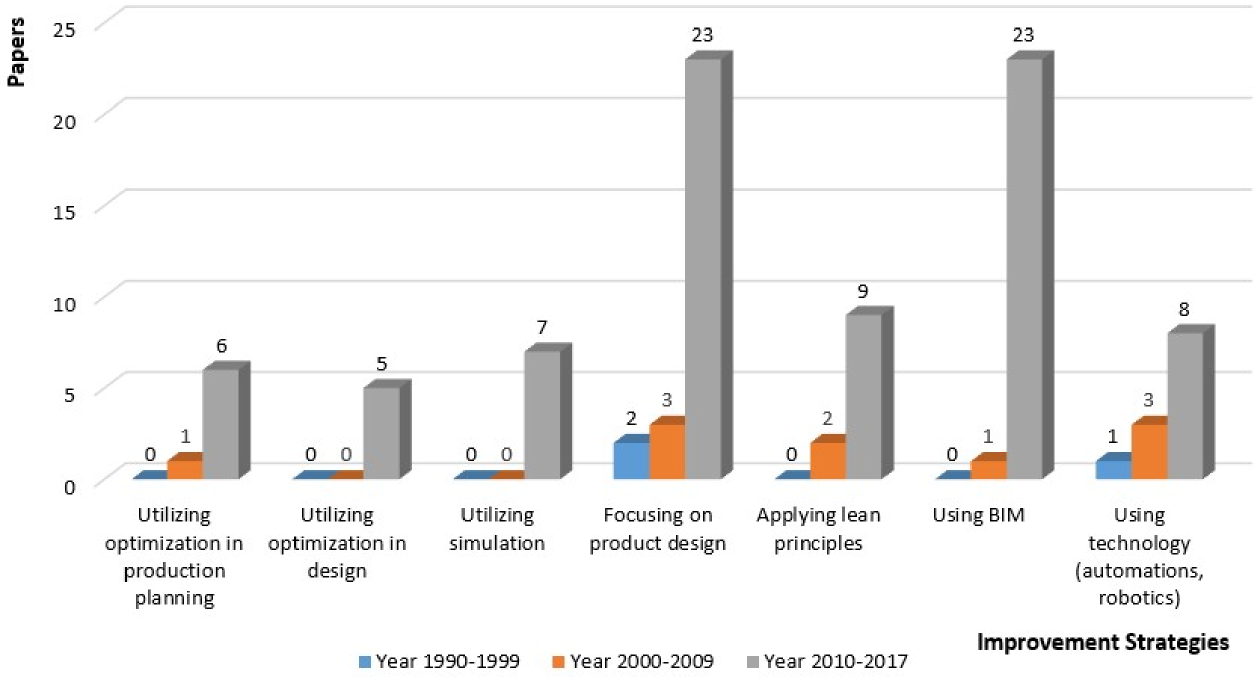


Figure 3.6 Strategies to improve CP&M supply chain

Utilizing Optimization in Design

Optimization has been applied in design to find the optimal configuration of CP&M components (Khalili and Chua, 2013; Said et al., 2017; Shahtaheri et al., 2017; Sharafi et al., 2017) or to find the optimal links of a structural network (Zawidzki and Nishinari, 2012). Khalili and Chua (2013) proposed an IFC (Industry Foundation Classes) based system to generate different configurations of precast elements in a building and used the mixed integer program to find the optimal configuration with minimal costs in mold fabrication, transportation and lifting. Shahtaheri et al. (2017) proposed a framework to find the optimal design of modular construction, with the variability in dimension and geometry by using a comprehensive tolerance strategy to minimize fabrication costs and risks. Said et al. (2017) develop an optimization model that utilized non-dominated genetic algorithm to support the design of panelized walls in building projects by finding the optimal geometry to minimize total cost and design deviation while meeting structural capability requirements. Sharafi et al. (2017) utilize the ant colony algorithm to search for the best spatial design in the early design stage of multi-story modular buildings. Zawidzki and Nishinari (2012) included a backtracking-based algorithm and evolution strategy-based algorithm to find the optimal links for a structural network created from truss-modules to connect any terminals in a provided environment with different obstacles. As most studies about utilizing optimization in design focused on finding optimal component configurations, future research could use interviews or surveys to identify other opportunities to utilize optimization into the design of CP&M systems.

Utilizing Optimization in Production Planning and Installation

Utilizing optimization into the production planning and installation of CP&M has been suggested in previous studies to reduce the cost and minimize the schedule. Most of the studies focus on optimizing schedules and resources (Anvari et al., 2016; El-Anwar and Kim, 2005; Kong et al., 2017; Zhang et al., 2014). Few studies address other areas in production planning and installation, such as determining the optimal prefabrication configuration and component grouping (Khalili and Chua, 2014) or minimizing waste in construction prefabrication (Banihashemi et al., 2017). Many scholars, including Anvari et al. (2016), Banihashemi et al. (2017), El-Anwar and Kim (2005), use the genetic algorithms to find optimal solutions. Besides addressing a single optimization objective, some studies also utilize multi-objective optimization models to illustrate the trade-off between different objectives in prefabrication production and installation such as cost and time (Anvari et al., 2016), or cost and environmental impact (El-Anwar and Kim, 2005). As the genetic algorithm has been commonly used to search for optimal solutions in construction prefabrication research, future studies could investigate how to utilize other optimization algorithms in addition to the genetic algorithm. Further studies should also explore other areas that may benefit from optimization, such as decision making about choosing prefabrication versus on-site construction or required conditions to successfully apply optimization into construction prefabrication.

Using Simulation

Simulation is used in a wide range of CP&M research areas to approximately imitate the operation of a process or a system. Examples of applying simulation in CP&M include evaluating an energy model (Abbood et al., 2015), analyzing a social network (Jiang, 2016), investigating assembly scenarios (Taghaddos et al., 2014) and testing construction planning scenarios (Liu et al., 2016). Abbood et al. (2015) propose a simulation model using EnergyPlus to evaluate a buildings' energy performance. Jiang (2016) use Social Network Analysis method to study the relationships between major stakeholders of the prefabricated housing system in China and proposed a prefabricated business ecosystem. Kong et al. (2017) develop a model to optimize the single-machine batch scheduling for the transportation and assembly of precast concrete and simulated a case based on a precast factory to test the model. Liu et al. (2016) propose a simulation model using Simphony software for the fabrication, transportation, assembly, and installation process of construction modules to evaluate different modular construction planning scenarios. Taghaddos et al. (2014) develop an integrated scheduling model for module constructions in an assembly yard that uses input from a comprehensive database to simulate the schedule and create different graphical reports. Although a simulation model may include simplified assumptions, it is helpful in providing insights about the potential behaviors of a CP&M process or a system for testing and learning purposes.

Focusing on Product Design

Focusing on product design is a strategy used in many studies to enhance the performance of the CP&M system. These studies addressed either the design of individual CP&M components/systems or the design of whole buildings.

The design of individual CP&M components discussed in the literature includes pipe racks, floor slabs, façade panels, composite walls and bridge piers. For example, Hua (2014) studies the design of pre-assembled pipe racks considering various conditions such as shopping, setting, lifting and fitting. Jensen at al. (2012) propose a customization process for the configuration of timber floor slab modules in a multistory timber building. Kilaire and Stacey (2017) discuss the design and installation of prefabricated double skin façade systems which could enhance customer comfort and reduce carbon emission. Malushte et al. (2009) present a new method to design modular composite walls under simultaneous thermal loads and transverse applied mechanical loads. Differing from the conventional method, the proposed method uses actual gradient instead of an equivalent linear thermal gradient to determine thermal loads. Pihelo et al. (2016) investigate the hygro-thermal risk for building envelopes before and after installing prefabricated modular elements on a case study project that consisted of large concrete panels and insulated by prefabricated modular elements. The study suggests ways to minimize impacts of hygro-thermal such as reducing the initial moisture content of concrete panels and using modular insulation panels with high thermal resistance and vapor permeability. Said et al. (2017) focus on the design of panelized walls in building construction and considered the panel geometry and structural capability. Soranio (2014) focuses on the design of prefabricated components to ensure material saving in fabricating and efficiency in assembling. Sung et al. (2017) propose a new precast segmental bridge pier system using the modular construction method. These studies provide a close examination and suggest improvement opportunities for particular building components/systems, contributing for the performance of the whole building projects.

Other studies address the product design on a broader scale such as the whole building. For example, Alwisy et al. (2012) propose to incorporate a computer model called MCMPro with BIM to generate shop drawings for the manufacturing of residential facilities. Hejtmanek et al. (2016) address the design prefabricated residential housing in the Czech Republic toward zero energy buildings. Jaksch et al. (2016) discuss the “Attic Adapt 2050” projects that develops the design and construction method of a prefabrication system comprising of renewable energy components and thermal efficiency envelop. Lapp and Golay (1997) discuss a methodology to systematically utilize modularization into the design and construction of nuclear power plants. Loss et al. (2016) and Loss and Davison (2017) investigate the design and construction of prefabricated steel-timber structures. Marchesi and Ferrarato (2015) propose to use Axiomatic Design to address the need to focus on the design of timber prefabricated buildings on the combination of customized and mass-produced parts to reduce cost and increase variety. Rausch et al. (2017a, 2017b) propose a dimensional variation analysis approach to reduce the overall assembly geometric deviation and avoid rework caused by component aggregation. Singh et al. (2015) present the development of rule-based BIM objects for the design of modular building components using BIM to streamline design process. Veld et al. (2015) present the development of MORE-CONNECT which involves the integration of prefabrication with multifunctional components for energy saving, building aesthetics, and efficient uses. Vural et al. (2007) propose modular houses that meet various needs of modern life and follow the vernacular architectural and climatic-topographic conditions. These studies focus on the design issues of CP&M in the building level, together with the studies addressing the design of individual components/systems, these studies provide a comprehensive overview of the product design of CP&M.

Applying Lean Principles

Lean principles have been used widely to improve construction productivity, including the CP&M domain. The literature review shows that various lean principles have been employed in this domain. To streamline the off-site fabrication of plumbing fixtures of two hospital case study projects, varying lean tools are utilized including value stream mapping, standardization, integrated form of agreement and BIM (Bekdik et al., 2016). Lean Six Sigma is used by Chowdhury (2016) to identify waste and cause of energy inefficiency in prefabrication and modularization. Legmpelos (2013) investigates the decision making in whether to use prefabrication for bathroom construction by applying “Choosing by Advantage” on a case study project. Yu et al. (2013) presents the development of a lean production in a modular building company that views the entire production line as a whole and focuses on stabilizing the production line instead of only focusing on the productivity of each operation.

Other studies address the application state of lean principles in the CP&M and their benefits. Bertelsen (2005) studies the relation between lean and prefabrication and confirmed that modularization is an approach to make construction lean. Olsen and Ralston (2013) interview 10 construction practitioners familiar with lean construction and prefabrication and find that: the selections of prefabricated assembly are based on best guesses because there is a lack of historical data; cost and schedule data are not tracked; although the selections of prefabricated assemblies should be from design stage, most of the selections are chosen during the preconstruction phase. O’Connor et al. (2015) study the relationship between modularization and design standardization and identify 10 forms of economic advantages and 3 forms of economic disadvantages. Senaratne (2010) study the application of lean methodology to construction prefabrication and identify 10 factors making prefabrication more efficient included: waiting time, inventory, moving, quality control, efficient testing, house-keeping, design reliability, technology, standardization, and human resources. These studies indicate a close relation between lean and CP&M, where lean could improve the performance of CP&M. On the other hand, CP&M could facilitate the adoption of lean practices. Nevertheless, there are still opportunities to improve the utilization of lean in CP&M as addressed by Bertelsen (2005) and O'Connor et al. (2015).

Using Building Information Modeling (BIM)

The development and utilization of BIM results in several benefits for the construction industry, including construction prefabrication and modularization. Many authors have studied the application of BIM to CP&M systems, such as civil and industrial projects (Alvarez-Anton et al., 2016; Parra and Bono, 2015; Rodrigues et al., 2016), for hospital projects (Bekdik et al., 2016), and for multi-stories buildings (Jensen at al., 2012; Solnosky et al., 2014). As per BorjeGhaleh and Sardroud (2016), applying BIM to the industrialization of building could be beneficial in term of cost, schedule and quality. Wu (2017) addresses how BIM and prefabrication can contribute to waste reductions via the 5 case studies including one hospital, two offices and two apartments. Abanda et al. (2017) investigated BIM's benefits and how using BIM can overcome the barriers hindering the utilization of off-site manufacturing. Korman and Lu (2011) discuss how BIM improved the modular MEP system. The benefits and challenges of implementing BIM into modular construction are also recognized by Lu and Korman (2010).

Other studies propose approaches to enhance the utilization of BIM in construction prefabrication and modularization such as using parametric modeling, laser scanning, and 3D point clouds. The benefit of parametric modeling in applying BIM for off-site construction design is discussed by Sharma et al. (2017). As per Banihashemi et al. (2017), parametric modeling could integrate with Rhino and Grasshopper software to minimize prefabrication waste. Singh et al. (2015) present the development of the rule-based BIM objects for the design of modular building components using BIM through the parametric modeling method to help streamline design process. Li et al. (2007) and Ramaji and Memari (2015) discuss the utilization of Industry Foundation Classes (IFC) and standardize information exchange methods for applying BIM into CP&M. A computer model called MCMPro is proposed by Alwisy et al. (2012) to integrate with BIM to generate shop and prefabrication drawings for the manufacturing of residential facilities. An approach using laser scanning, 3D point clouds and 3D CAD model to remotely assess the quality of prefabricated steel assembly is suggested by Nahangi et al. (2014).

Applying Advanced Technologies

A number of studies have investigated how to enhance CP&M performance through advanced technologies such as robotics (Kasperzyk et al., 2017; Li et al., 2007; Neelamkavil, 2009; Ueno, 1994), RFID – Radio frequency identification (Li et al., 2017a), laser scanning (Nahangi et al., 2014; Safa et al. 2015), 3D printing or additive manufacturing (Krimi et al., 2017), internet of things, and 3D point cloud (Li et al., 2016; Xu et al., 2015; Zhong et al., 2017).

Application of automations into CP&M systems gained a significant interest in the literature. Kasperzyk et al. (2017) present a robotic prefabrication system (RPS) which can automatically disassemble a fabricated structure and reconstruct it according to a new design. This system has been validated successfully on two lab-scaled fabricated structure. Li et al. (2007) present the application BIM to the prefabrication of a wall system and suggested that a robot could be used as a CNC machine to automatically cut stone into pieces per designed. Neelamkavil (2009) provides an overview of the prevalent automations in construction prefabrications and found three prime areas of prefabrication automations including: design (3-D modeling), material handling (robotics), and business processes (include planning and scheduling). A Japanese view on the role of automation and robotics in construction is presented by Ueno (1994). The study suggests that to widely apply automation and robotics in the construction industry, building elements should be pre-fabricated and the working space should be weather protected.

Other studies focused on Radio frequency identification (RFID), 3D laser scanning, 3D printing, internet of things, and 3D point cloud. RFID is proposed by Li et al. (2017a) through a platform to integrate RFID and BIM technology to mitigate risks and improve schedule performance of prefabricated housings. The platform is helpful in enabling real-time information flows and facilitating coordination from prefabrication manufacturing to logistics and on-site assembly. 3D laser scanning is studied by Nahangi et al 2014 and Safa et al. 2015. Nahangi et al. (2014) present an approach using laser scanning, 3D point clouds and 3D CAD model to remotely assess the quality of prefabricated steel assembly. Safa et al. (2015) present the application of 3D laser scanning and photogrammetry techniques for quality assurance process of prefabricated pipe spools. 3D printing is addressed by Krimi et al. (2017) when they compare conventional construction with additive manufacturing. Conventional construction as a construction method includes prefabrication and casting on site, while additive manufacturing is a method that builds an object from layer to layer through 3D CAD model. The study (Krimi et al., 2017) concludes that additive manufacturing has an advantage in increasing freedom of design, but in some cases, pre-casting may be faster than additive manufacturing. Li et al. (2016) propose an internet of thing-based platform to enhance the management of prefabrication housing production in Hong Kong. Xu et al. (2015) suggest a cloud asset-enable prefabrication transportation service to facilitate the transportation of precast components. This service allows different stakeholders in prefabrication transportation to make decisions efficiently based on collected real-time data. Zhong et al. (2017) propose the implementation of a multi-dimensional internet of things-enabled BIM platform into construction prefabrication to achieve real-time visibility and traceability. This platform can capture real-time data to allow end-users to monitor a project's status and accumulated cost.

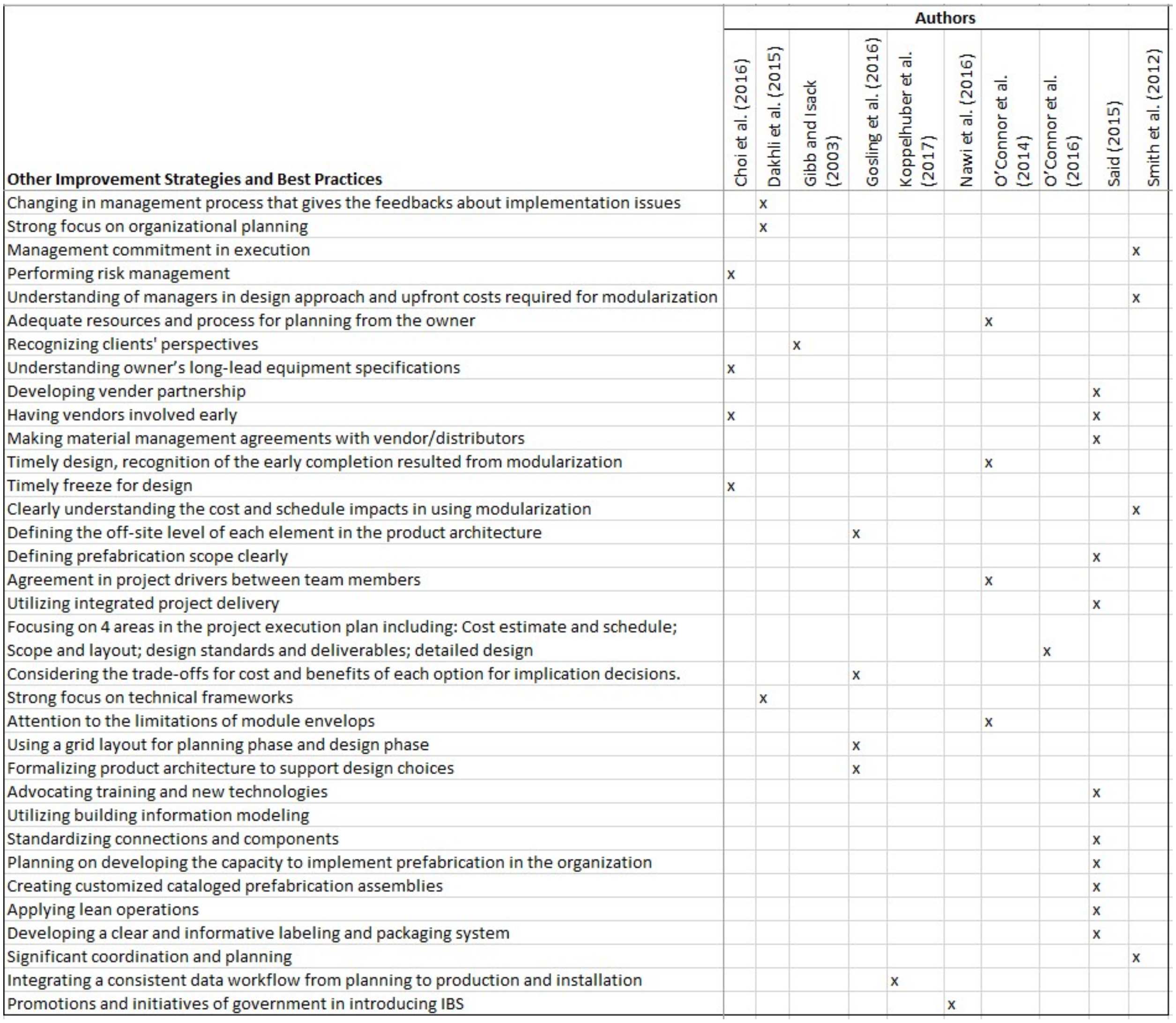
Other Improvement Strategies and Best Practices

In addition to the strategies listed above, many best practices for the implementation of prefabrication in construction have been suggested in the literature such as focusing more on technical frameworks, changing in organizational planning (Dakhli et al. 2015), involving suppliers in early design process (Gibb and Isack 2003), paying significant efforts on coordination and planning (Smith et al. 2012), etc. Table 3.4 lists out the best practices suggested in the literature. Findings of all related papers are also presented below.

The critical success factors for cost and schedule performance of modularization projects is proposed by Choi et al. (2016) including timely design, owner's long-lead equipment specification, involvement of vendors and risk management. The key considerations to implement modularization are investigated by Dakhli et al. (2015) via two case study projects, including an educational building and a residential building. Their study indicates that modularization should be accompanied with a change in organizational planning and management processes with a strong focus on technical frameworks. Gibb and Isack (2003) discuss the drivers of pre-assembly in the perspectives of clients and state that more than half of the interviewed clients expected to have more pre-assembly in their project, and pre-assembly supply chains should recognize clients' perspectives to capitalize this opportunity. Gosling et al. (2016) study 15 projects using modularization in Italy, Germany, Brazil and the United Kingdom to capture the meanings, perceptions, and definitions of modularization in building projects. In this study, the authors also develop a guide to organize project activities to adopt modularization effectively. The guide includes a four-step approach for modular design and off-site strategy including: use a grid layout for the planning phase and design phase; formalize product architecture to support design choices; define the off-site level of each element in the product architecture; and consider the trade-offs for the cost and benefits of each option for implication decisions. A survey on 28 experts in architecture, engineering, construction and investment is conducted by Koppelhuber et al. (2017) to identify the advantages, constraints, and challenges of industrialized timber building system. This study suggests that consistent data workflow needs to be incorporated from planning to production and installation processes to enhance the performance of industrialized timber building systems.

The top five critical success factors for implementing prefabrication are suggested by O'Connor et al. (2014) including: attention to the limitations of module envelops, the agreement in project drivers between team members, adequate resources and process for planning from the owner, timely design, recognition of the early completion resulted from modularization. O'Connor et al. (2016) identify 107 differences in how modular projects should be planned and implemented in comparison with conventional projects and suggested that execution plan is one key leading to the successful implementation of modularization. The key points for the successful application of modularization in nuclear power projects is suggested by Smith et al. (2012): clearly understanding the cost and schedule impacts in using modularization; significant coordination and planning may be required up to three years prior to the construction; management commitment is crucial for successful execution; managers must clearly understand the design approach and upfront costs required for modularization strategies.

Table 3.4 Other improvement strategies and best practices for CP&M



	Authors									
Other Improvement Strategies and Best Practices	Choi et al. (2016)	Dakhli et al. (2015)	Gibb and Isack (2003)	Gosling et al. (2016)	Koppelhuber et al. (2017)	Nawi et al. (2016)	O'Connor et al. (2014)	O'Connor et al. (2016)	Said (2015)	Smith et al. (2012)
Changing in management process that gives the feedbacks about implementation issues		x								
Strong focus on organizational planning		x								
Management commitment in execution										x
Performing risk management	x									
Understanding of managers in design approach and upfront costs required for modularization										x
Adequate resources and process for planning from the owner							x			
Recognizing clients' perspectives			x							
Understanding owner's long-lead equipment specifications	x									
Developing vender partnership									x	
Having vendors involved early	x								x	
Making material management agreements with vendor/distributors									x	
Timely design, recognition of the early completion resulted from modularization							x			
Timely freeze for design	x									
Clearly understanding the cost and schedule impacts in using modularization										x
Defining the off-site level of each element in the product architecture				x						
Defining prefabrication scope clearly									x	
Agreement in project drivers between team members							x			
Utilizing integrated project delivery									x	
Focusing on 4 areas in the project execution plan including: Cost estimate and schedule; Scope and layout; design standards and deliverables; detailed design								x		
Considering the trade-offs for cost and benefits of each option for implication decisions.				x						
Strong focus on technical frameworks		x								
Attention to the limitations of module envelops							x			
Using a grid layout for planning phase and design phase				x						
Formalizing product architecture to support design choices				x						
Advocating training and new technologies									x	
Utilizing building information modeling										
Standardizing connections and components									x	
Planning on developing the capacity to implement prefabrication in the organization									x	
Creating customized cataloged prefabrication assemblies									x	
Applying lean operations									x	
Developing a clear and informative labeling and packaging system									x	
Significant coordination and planning										x
Integrating a consistent data workflow from planning to production and installation					x					
Promotions and initiatives of government in introducing IBS						x				

3.4 SUMMARY

This chapter presents an extensive literature review of 110 papers related to construction prefabrication and modularization (CP&M) published during 1990 and 2017 to identify the research trends in this domain and the improvement strategies suggested in the literature for CP&M supply chain. Previous studies have suggested various improvement strategies such as utilizing optimizations, using simulation, focusing on product design, applying lean principles, using BIM and exploiting advanced technologies. Prior studies also propose different best practices relating to execution plans, management perspectives, vender issues, coordination and training to enhance the CP&M performance. This literature review recognizes a growing trend in the research about CP&M as the number of studies relating to this area has increased exponentially in recent years. The country that contributed the most research papers is the U.S., followed by China, Canada and then Australia. The most interested sectors are the residential sector and the civil industrial sector. The material/system addressed most in the literature are concrete and steel structures. A majority of studies suggest utilizing BIM and focusing on product designs are strategies to improve the CP&M supply chains. Further research regarding CP&M should focus on areas that have not received adequate attention such as optimization of design and production planning, healthcare sectors, and prefabricated rebar material.

Construction prefabrication modularization is a growing trend in the construction industry and many studies have investigated this supply chain. This literature review is necessary to identify the potential improvement opportunities suggested in the literature for CP&M supply chains, and to identify future research opportunities in this area. Although the review has included the related studies compiled in the common research databases, it may not be entirely comprehensive provided that some other studies may be available beyond these databases.

Chapter 4. INDUSTRY SURVEY

Overview: In order to understand the current practices in operating prefabrication supply chain system, I conducted two surveys, each one with six prefabrication contractors in the Pacific Northwest. The first survey was done in 2017, and the second survey in 2018-2019. The first one was a preliminary survey focusing on the general operation of CP&M supply chains and the potential needs for improvement. The second survey was an extension of the first one, and it included a set of interview questions to understand the operation of CP&M supply chains, improvement opportunities, but adding the impact of uncertainty on CP&M supply chains. This chapter presents the content and findings of these surveys.

4.1 FIRST SURVEY

This survey was carried out in 2017 with six fabricators: one façade contractor, three rebar fabricators, one mechanical and two electrical and plumping (MEP) contractors. The survey comprised of interviews with these fabricators at their office, and each intereview was followed by a factory tour to understand the workflow at their factory. The interviewees were the personnel who are experienced in the operation of their prefabrication supply chain, including one company president, one operations manager, two shop managers, one sale manager and two project managers. From the first survey, I acquired basic information about the shop conditions, leading time and inventory. I noted that two of the surveyed fabricators operate multiple fabrication shops and allocate jobs and inventory between these shops. I also learned that these fabricators mostly use Microsoft Excel spreadsheet to develop shop schedules and never utilized optimization into their production. This motivated me to investigate the application of optimization to assist this supply chain and carried out the second survey to learn more about their production plan, demands from construction projects, and impacts of uncertainty on their production plan.

4.2 SECOND SURVEY

This survey was carried out from 2018 to 2019 with six fabricators: one rebar fabricator, two MEP contractors, one stone contractor, one exterior panel contractor and one precast concrete contractor. One rebar fabricator and one MPE contractor participated in both the first and the second surveys.

Similar to the first survey, the second survey also included direct interviews and factory visits. The interviewees were the personnel who are experienced in the operation of their prefabrication supply chains such as shop managers, project managers and operations managers. A list of interview questionnaires was sent to the fabricators before conducting the interview. The interviewees could either type the answer into the interview questionnaire file or answer the questions directly during the interview. Almost all interviews were followed with a factory tour to observe and get a better understanding of the workflows, machines and production activities in the factory. One interview was conducted via tele-conference and one interview was conducted via email.

The interview questionnaires are included in Appendix 1 of this dissertation. The interviews included open-ended questions focusing on the following areas:

- Shop conditions: to study working schedule, number of shop workers and available machines.
- Shop operations: to study inventory, leading time, holding time, handling cost, tracking of productivity, how to develop and manage production schedule.
- Job demand: to study how prefabricators communicate with general contractors about job demand.
- Required delivery time: to study how reliable the demand about required delivery times is and how to reduce the impact of variable required delivery times.
- Application of optimization: to study the awareness of prefabrication contractors about optimizations and potential application of optimization into prefabrication supply chain.

4.3 SURVEY FINDINGS

Through the surveys, I found that adopting lean production to improve the workflow is a common goal for these companies. All surveyed companies apply Just-in-Time (JIT) and pull the demand from the construction sites to process the production in fabrication shops. Finished products are typically stored in the factory for one to five days before being delivered to jobsites. This practice helps construction fabricators reduce handling costs and avoid running out of storage area. Fabricated materials can be transported to job sites for assembly and installation or assembled in the fabrication shops. The availability of machines, workforce, and assembly area nearby the fabrication shops allows these fabricators to efficiently perform the modularization if it is required by construction projects. Although prefabrication and modularization are increasingly applied in the construction industry, the level of off-site versus on-site work varies between different building systems. In the first survey, I found that the off-site labor percentage for the curtain wall company is 70%, 50% for the rebar fabricators, and 20% for the MEP companies. These numbers explain how the unique characteristics of different building systems impact the level of prefabrication; they also show that there is an opportunity to increase the level of prefabrication for certain trades such as MEP. As the off-site labor percentage for the MEP companies is relatively low, future research may focus on what this trade could do to increase the off-site work level and how optimization could support this effort.

The findings regarding above areas of interests mentioned in Section 3.3 are:

- Shop conditions: The survey indicates that most fabricators work 5 days per week, 1 shift per day and 8 hours per shift. Three fabricators have very high workload that requires to work 6 days per week, 2 shifts per day and 8-10 hours per shift. The number of shop workers ranges from 5 to 70 and the number of machines ranges from 5 to 50.
- Shop operations: I found that most prefabrication shops have a safe amount of inventory to avoid material shortage. Sometimes they buy materials in a large amount to avoid the impact of price fluctuations, or buy materials in an annual package, but only transport to the shop periodically when needed. Most fabrication shops finish the fabricated products 2-5 days prior to delivering to construction projects in order to reduce storage and handling cost. Production schedule is prepared by shop managers, and most of them use Microsoft Excel spreadsheet to develop production schedules. Using barcodes to keep track of materials and inventory is common in construction prefabrication. However, few of them utilize radio frequency identification (RFID), laser scanners, and none of them apply robotics into their production process. Three out of ten contractors confirmed that they track the productivity of machine and labor, but none of them were willing to provide productivity data, maybe because this information is essential and confidential.

- Job demand: The survey shows that the fabricators communicate about their shop demands via their field personnel. They have staffs participating in weekly meetings, daily meetings or periodic meetings at construction sites to communicate with main contractors about project schedules and inform back to the shop people.
- Required delivery time: It is common that the construction projects change schedule and vary their required delivery time of prefabricated products. However, only one of the interviewed fabricators tracks the changes. The fabricator indicated that about 30% of their works are requested to change the required delivery time. While postponing the required delivery time of products happens more often, sometimes it is shifted to earlier dates. Changing the required delivery time when the shop production is already planned, or at the middle of the performance of the planning period may force the prefabricator to utilize more resources such as workers, machines and materials to handle the changes, incurring more cost for prefabrication supply chains. However, in most cases, the fabricators must bear the cost by themselves. Nevertheless, the fabricators need to estimate the potential cost incurred by these changes and add it to their proposed cost from bidding process, leading to an increased cost for construction projects.
- Application of optimization: The survey revealed that none of the interviewed fabricators has applied optimization into their production. However, most of them think that optimization would benefit their production systems, but they are not willing or not ready to adopt it. I also found that the application of optimizations could be convenient or challenges depending on prefabrication systems and fabrication shops. It could be convenient to utilize optimization for prefabrication systems like curtain walls, exterior wall panels, fabricated rebars because the number of unique job parts are not too large and workflows are quite consistent, leading to an acceptable number of rules for constraints. However, it is more challenging to utilize optimization for MEP system because of the thousands of unique of job parts with different workflows in MEP systems, leading to an enormous constraint rules for the optimization model. Further research is needed to study the work break-down structures and work sequences of MEP systems as well as other CP&M systems to determine how to effectively apply optimization into these systems.

The survey results also revealed that two out of the six prefabricators operate multiple fabrication shops in order to meet market demand while reducing the cost, and two other prefabricators plan to open a second fabrication shop to meet their market expansion. One MEP contractor has three fabrication shops in the Pacific Northwest, and one of the rebar fabricators has more than ten fabrication shops across the U.S. Strategically locating their facilities helps these companies become more responsive to market demand, reduce transportation costs, and lower the risks of shortages in materials and workforce. These fabricators also allocate inventory between their fabrication shops in some cases to address the lack of materials or price fluctuations. Factors that impact allocation decisions include travel distances between the shops and job sites; shop capacities such as the availability of inventory, machine, workforce; job demands on schedule and quantity; weather conditions and geographic conditions; and availability of shipping trucks. Normally, a construction project (a job) demands several types of prefabricated materials (job parts) which may be fabricated and/or assembled at different fabrication shops. Supply chain managers decide how to allocate these jobs and job parts through the information gained from daily communication. Although the job allocations could be complicated, these fabricators rarely quantify the cost or time impact of the allocation decisions and haven’t used any optimization models to find an optimal solution.

4.4 SUMMARY

This chapter presents the industry surveys that I have carried out to understand the current practices in production operations of CP&M supply chains, the potential of applying optimization into the production planning of these supply chains and the impact of demand uncertainty about required delivery time to the performance of CP&M supply chains. It reveals the general information about shop conditions such as labor, machine, working time, inventory, storage of prefabrication shops and the method that they use for production planning. The surveys indicate that optimization is uncommon with the interviewed prefabricators, but they still expect to utilize it in the future. Although many fabricators are managing multiple fabrication shops, few quantitative models are available to supply the production planning and job allocations between the shops for these fabricators. Finally, the surveys show that it is common for construction projects to change schedule and request to change the delivery time of prefabricated products, making it difficult for fabricators to adjust the production plan and causing an increased cost.

Chapter 5. PRODUCTION PLANNING OF CP&M SUPPLY CHAINS WITH MULTIPLE SHOPS UNDER DETERMINISTIC CONDITION

Overview: Although many prefabrication companies are operating multiple fabrication shops at different regions and allocate jobs and inventory between these shops, few quantitative models are available to facilitate the job and inventory allocation between the shops. This chapter presents an optimization-based decision-support model for production planning and job allocations that incorporates job assignments and shop scheduling. This chapter also discusses computational results on an example problem that saves 2.5% of the total cost compared to the traditional Early Due Date (EDD) method. The example problem indicates that demand variations could cause a 4.39% increase in the total cost. Moreover, this chpater introduces a sensitivity analysis to quantify the impacts of parameters sensitive to supply chain performance. The content presented in this chapter is mostly from a paper written by Ho et al. (2019) that has been submitted to the Journal of Construction Engineering and Management and is under review.

5.1 BACKGROUND

The literature has widely addressed the planning and scheduling of a supply chain network with multiple facilities and stages. Arntzen et al. (1995) presents a large mixed-integer linear program named Global Supply Chain Model, which is developed to minimize cost, production, and distribution times while meeting the demands and restriction of local areas and the capacities of a global manufacturing and distribution network. Pinedo (2009) proposed optimization models for the planning and scheduling of supply chains that include multiple stages and facilities at the tactical level and operational level. Javid & Azad (2010) develop a model that simultaneously optimized location, allocation, capacity, inventory and routing of a stochastic supply chain system. Zadeh et al. (2014) propose a design of steel supply chain networks to support a country-wide planning in production, inventory, distribution, and capacity expansion. Yu et al. (2015) focus on a multi-echelon supply chain comprised of suppliers, plants, and distribution centers and develop a model aiming at selecting locations to build plants and distribution centers at minimal total cost. These studies indicate that integrating optimization into planning and scheduling can help reduce cost and time.

Although the CP&M supply chains with multiple fabrication shops have become popular in the construction industry, few studies have paid attention to this type of supply chain system. Unlike other industry sectors, construction products are job-specific, making it difficult to apply the optimization models that have been developed for other industries. Several studies have offered solutions to optimization problems related to job shop schedule, inventory, and cost for individual construction fabrication shops (Chan & Hu, 2001; Leu & Hwang, 2002; Pan et al., 2011; Tserng et al., 2011; Shu et al., 2014; Matt et al., 2015; Anvari et al., 2016). However, there has been little research on supply chain planning and the coordination between multiple fabrication facilities. El-Anwar and Kim (2005) propose a multi-objective optimization model for a pre-fabricated rebar supply chain with multiple assembly centers but his model does not offer a way to incorporate job allocations into shop schedules.

Given the increased demand in construction prefabrication and modularization (CP&M) and the lack of studies supporting the planning and scheduling of prefabrication supply chains with multiple fabrication shops, my research fills an important gap. This research presents the application of optimization in assisting job allocations between different fabrication shops while considering transportation distances and shop capacities. I also discuss the effect of demand variations and introduce a method that identifies the parameters sensitive to supply chain performance and quantifies their impact. In addition, this study verifies the effectiveness of the optimization solution by comparing it with the solution generated from the traditional Early Due Date method. The following sections describe an optimization model, offer a detailed example problem, provide the computational results of the example problem and finally, discuss the findings.

5.2 JOB ALLOCATIONS OF CP&M SUPPLY CHAINS WITH MULTIPLE SHOPS

The survey presented in Chapter 4 reveals that two out of the surveyed fabricators operate multiple fabrication shops in order to meet market demand while reducing the cost, and two other fabricators are planning on opening a second fabrication shop to meet their market expansion. Locating their facilities strategically helps these companies become more responsive to market demand, reduce transportation costs, and lower the risks of shortages in materials and workforce.

Supply chain managers need an optimization model to facilitate the allocation of jobs and inventories. Operational data about job requirements and shop conditions is usually stored in Excel spreadsheets; however, there is no comprehensive calculation model available to help the managers to quantify the outcome of allocation decisions. While optimization models could be beneficial in reducing the impact by prioritizing local materials, designing appropriate batch sizes for truck loads, and reducing transportation distances, little attention has been paid to this opportunity. Making allocation decisions without using any calculation models may result in lost opportunities to reduce cost and delay. An optimization model that facilitates the decision-making about the allocation of jobs and inventories would advance the operation of construction prefabrication and modularization of supply chains and benefit construction projects.

Figure 5.1 presents the flows of jobs and inventories in a multiple fabrication shop network. In this figure, jobs are construction projects situated at various locations. Each job can contain various job parts that may be fabricated and/or assembled at different fabrication shops.

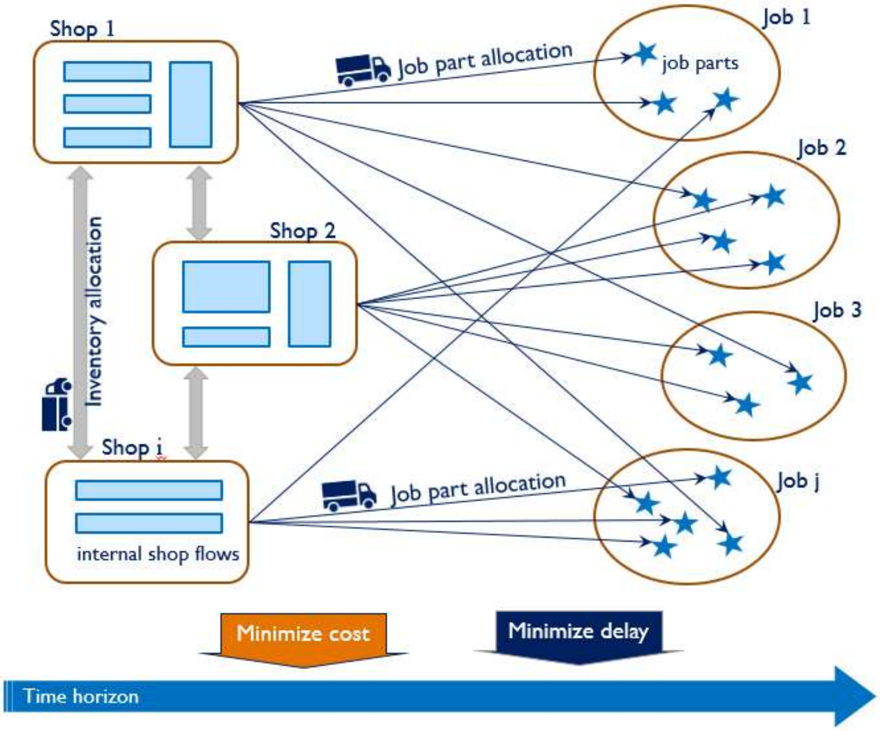


Figure 5.1 Allocation of jobs and inventories in CP&M supply chain with multiple shops

An optimization model is developed focusing on allocating jobs between fabrication shops and determining production schedules in order to minimize cost and delay. The model is solved using CPLEX (Version 12.7, 2016) and tested with different variables to verify its accuracy. The next sections present the mathematical model and an application of the model to an example problem.

The model was created for a CP&M supply chain that operates multiple fabrication shops based on the following assumptions:

1. The supply chain is designed to provide prefabricated materials for different construction projects (jobs).
2. Each construction project may require different prefabricated items (job parts).
3. Each fabrication shop has machines and labor that can process all types of job parts required by the construction projects.
4. Each type of job part is processed by a single machine.
5. Each fabrication shop has one machine for each type of job part.

6. Each fabrication shop has an unlimited storage capacity and includes inventory costs in unit production costs.
7. The supply chain has enough inventory at each shop and does not need to allocate inventory amongst the shops.
8. The supply chain has an unlimited transportation capacity that could transport all prefabricated items to each job site within one day.

5.3 OPTIMIZATION MODEL

The optimization model incorporates multiple consecutive stages of the supply chain in both overall supply chain level and shop level. The incorporation of planning and scheduling at the supply chain level and shop level has been addressed in manufacturing research (Arntzen et al., 1995; Pinedo, 2009; Zadeh et al., 2014). While the planning of a supply chain usually covers multiple stages (or facilities) in a medium-term horizon, the scheduling normally focuses on a single stage (or a facility) in a short-term horizon. Planning the supply chain may consider the distinction between production families, but usually ignores the distinction between different products in a family. In contrast, scheduling of the shop requires more detailed information, including characteristics of each job or product. Nonetheless, the planning and scheduling of production, inventory, and transportation are usually closely interconnected, and it is useful to incorporate them into a single framework for practical purposes (Pinedo, 2009). In my optimization model, jobs and job parts are assigned to different fabrication shops based on shop capacities and transportation distances. At the same time, the schedules of these fabrication shops are designed and optimized to accommodate the job allocations as assigned by the supply chain network.

In the optimization model, a job corresponds to a construction project that generates the demand for fabricated and/or assembled materials. A job may include a set of job parts with varying delivery times. To develop and implement prefabrication schedules, shop managers need to consider factors such as machines, labor, and inventory. Since Just-in-Time is a common practice in construction prefabrication/modularization in which materials are fabricated and assembled just a few days before delivery time, I assume that these fabrication shops always have sufficient storage capacity.

The objective of this optimization model is to minimize the total cost of production, transportation, and tardiness. Minimizing the total cost of transportation distance typically leads to a reduced overall cost. However, in case the nearest shop does not have enough production capacity, jobs will be assigned to another shop. As a result, the supply chain can achieve other objectives, such as minimizing the delay in delivery. The optimization model includes sets, variables, and parameters as follows:

Sets

I: Set of fabrication shops.

J: Set of jobs.

K: Set of job parts.

T: Set of time intervals (days) in the time horizon.

Variables

x_{ijkt}: Quantity (in units) of job part k in job j produced at fabrication shop i in time interval t for $i \in I,\ j \in J,\ k \in K,\ t \in T$.

y_{ijkt}: The quantity of job part k transported from the fabrication shop i to the construction site of job j at time t for $i \in I,\ j \in J,\ k \in K,\ t \in T$.

v_{jkt}: The quantity (in units) of job part k that is tardy (have not arrived) at job j at the end of time interval t for $j \in J,\ k \in K,\ t \in T$.

Parameters

$D_{\mathrm{j}k}$: Demand (in units) for job part k in job j for $k \in K, j \in J$.

a_{jk}: The due date of job part k of project j for $k \in K, j \in J$.

h_{ik}: Processing time (in hours) for job part k at fabrication shop i for $i \in I,\ k \in K$.

$\tilde{h}$: Number of machine hours per day available for production.

t^{end}: The last day in the considered time horizon.

c_{ik}^{p}: The cost to process a unit of job part k at fabrication shop i for $i \in I,\ k \in K$.

$c_{k}^{p_{tardy}}$: The estimated cost to process a unit of job part k that is still delayed at the end of the time horizon for $k \in K$.

c_k^m: The cost to transport one unit of job part k for one km transportation distance for $k \in K$.

d_{ij}: Transportation distance (in km) from fabrication shop i to the construction site of job j for $i \in I,\ j \in J$.

d_j^{tardy} : Estimated transportation distance (in km) from a fabrication shop to the construction site of job j for the job parts that are still tardy at the end of the time horizon for $j \in J$.

w_{jk}: The tardiness (delay) cost per unit per day for an order of job part k of project j that is delayed $j \in J,\ k \in K$.

To minimize the total cost, the optimization model is formulated as follows:

Minimize total cost C:

$$C = \sum_{t\in T}\sum_{k\in K}\sum_{j\in J}\sum_{i\in I} c_{ik}^{p}\ x_{ijkt} + \sum_{t\in T}\sum_{k\in K}\sum_{j\in J}\sum_{i\in I} c_k^m\ y_{ijkt} d_{ij} + \sum_{t\in T}\sum_{k\in K}\sum_{j\in J} w_{jk}\ v_{jkt}$$

$$+ \sum_{j\in J}\sum_{k\in K} c_k^{p_{tardy}}\ v_{jkt^{end}} + \sum_{j\in J}\sum_{k\in K} c_k^m\ v_{jkt^{end}}\ d_j^{tardy}$$

Subject to the constraint in the availability of machine at fabrication shops:

$$\sum_{j\in J} h_{ik} x_{ijkt} \le \tilde{h} \qquad i \in I \quad t \in T \quad k \in K$$

Subject to the constraint in the tardy job:

$$\sum_{\tau=1,\ldots,t}\ \sum_{i\in I} y_{ijk\tau} + v_{jkt}\ = D_{jk} \qquad t \ge a_{jk} \quad j \in J \quad k \in K$$

Subject to the constraint in the total transportation quantity:

$$\sum_{t\in T}\sum_{i\in I} y_{ijkt} = \sum_{t\in T}\sum_{i\in I} x_{ijkt} \qquad j \in J \quad k \in K$$

Subject to the constraint in the transportation at each day in the time horizon:

$$\sum_{\tau=1,\ldots,t}\ \sum_{i\in I} y_{ijk\tau} \le \sum_{\tau=1,\ldots,t}\ \sum_{i\in I} x_{ijk\tau} \qquad j \in J \quad k \in K \quad \mathrm{t} \in T$$

Subject to the constraint in the non-negative properties of the integer variables:

$$x_{ijkt}, y_{ijkt}, v_{jkt} \in \{0,1,2,\ldots\} \qquad i \in I \quad j \in J \quad k \in K \quad t \in T$$

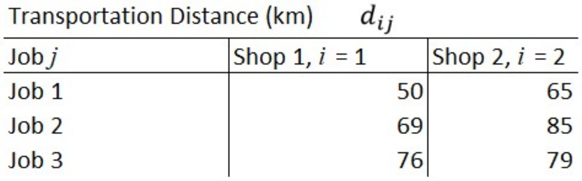
In this problem, the variables such as processing quantities, transportation quantities, and tardiness quantities are integers. The objective of the model is to minimize the cost function which includes a processing cost $\sum_{t \in T} \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} c_{ik}^{p} \; x_{ijkt}$, a transportation cost $\sum_{t \in T} \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} c_k^m \; y_{ijkt} d_{ij}$, a penalty cost for delayed quantities $\sum_{t \in T} \sum_{k \in K} \sum_{j \in J} w_{jk} \; v_{jkt}$, processing cost for the unmatched demand quantities at the end of the planning period $\sum_{j \in J} \sum_{k \in K} c_k^{p_{tardy}} \; v_{jkt^{end}}$, and a transportation cost for the unmatched demand quantities at the end of the planning period $\sum_{j \in J} \sum_{k \in K} c_k^m \; v_{jkt^{end}} \; d_j^{tardy}$.

To test the performance of this optimization model, I developed an example problem for a prefabrication supply chain with two fabrication shops and three construction projects. The next sections present the example problem and the computational results.

5.4 EXAMPLE PROBLEM

The optimization model is demonstrated through the following example problem. Consider a 4-week planning period (28 days) of a prefabrication supply chain network that includes two fabrication shops and three construction projects (three jobs) situated at different locations. Each fabrication shop could fabricate all types of unique job parts. Each job requires 5 different types of job parts at different days in the 4-week-planning horizon. The total number of unique job parts demanded by these jobs is 8. The processing time and cost to process each job part are different between fabrication shops. Each fabrication shop operates eight hours per shift, two shifts per day, seven days per week. As a result, the number of machine hours available to produce each job part daily is $\tilde{h}$= 16. The supply chain managers need to determine how to assign the job parts of each construction project to different fabrication shops, the time to start the production at the fabrication shops, and the time to deliver finished products to construction sites. Tables 5.1 to 5.3 describe the input data of this example problem.

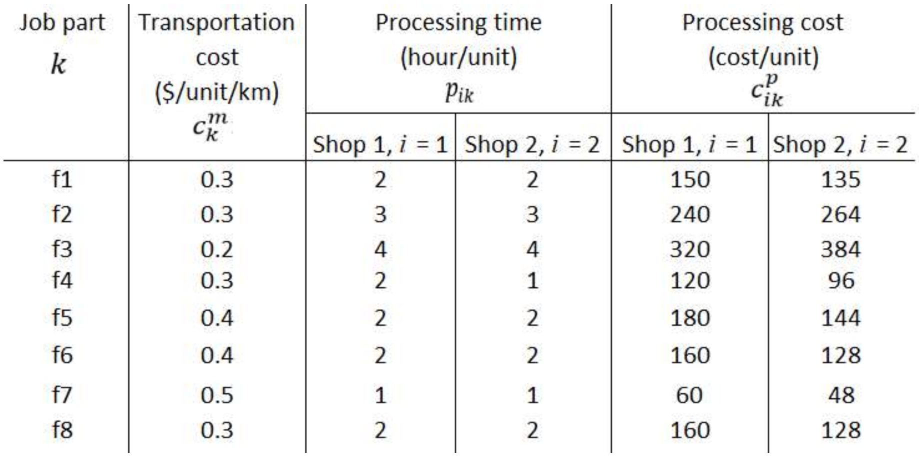
Table 5.1 Distance between fabrication shops and construction sites



Transportation Distance (km) d_{ij}

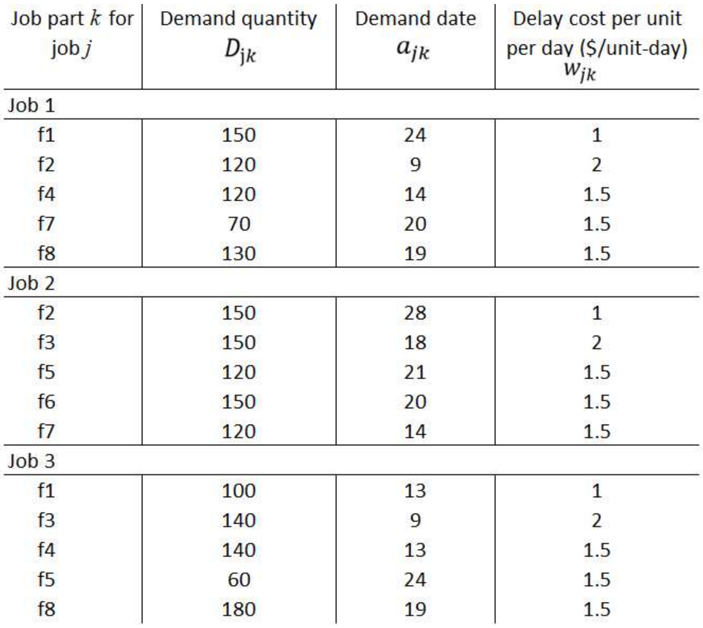
Job j	Shop 1, i = 1	Shop 2, i = 2
Job 1	50	65
Job 2	69	85
Job 3	76	79

Table 5.2 Transportation cost, processing time, and processing cost of job parts



Job part k	Transportation cost (\$/unit/km) c_k^m	Processing time (hour/unit) p_{ik}		Processing cost (cost/unit) c_{ik}^p	
		Shop 1, i = 1	Shop 2, i = 2	Shop 1, i = 1	Shop 2, i = 2
f1	0.3	2	2	150	135
f2	0.3	3	3	240	264
f3	0.2	4	4	320	384
f4	0.3	2	1	120	96
f5	0.4	2	2	180	144
f6	0.4	2	2	160	128
f7	0.5	1	1	60	48
f8	0.3	2	2	160	128

Table 5.3 Demand on job parts of each job

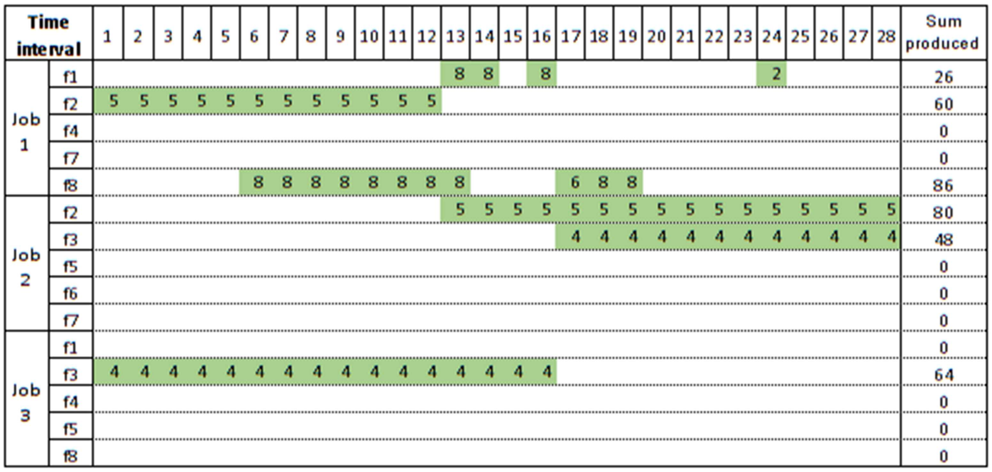


Job part k for job j	Demand quantity D_{jk}	Demand date a_{jk}	Delay cost per unit per day (\$/unit-day) w_{jk}
Job 1			
f1	150	24	1
f2	120	9	2
f4	120	14	1.5
f7	70	20	1.5
f8	130	19	1.5
Job 2			
f2	150	28	1
f3	150	18	2
f5	120	21	1.5
f6	150	20	1.5
f7	120	14	1.5
Job 3			
f1	100	13	1
f3	140	9	2
f4	140	13	1.5
f5	60	24	1.5
f8	180	19	1.5

5.5 COMPUTATIONAL RESULTS

The optimization model is solved using CPLEX optimization software package (CPLEX version 12.7, 2016). In this example problem, CPLEX reads the input data from an Excel file and writes the output to another Excel file. It takes approximately 17 seconds for CPLEX to run the optimization model in an Intel® Core™ i7-5500U CPU@2.40GHz laptop. The optimal cost obtained from the model is $377,484. The optimal solution including production schedule, transportation schedule, and delayed quantities is presented in Tables 5.4 to 5.8.

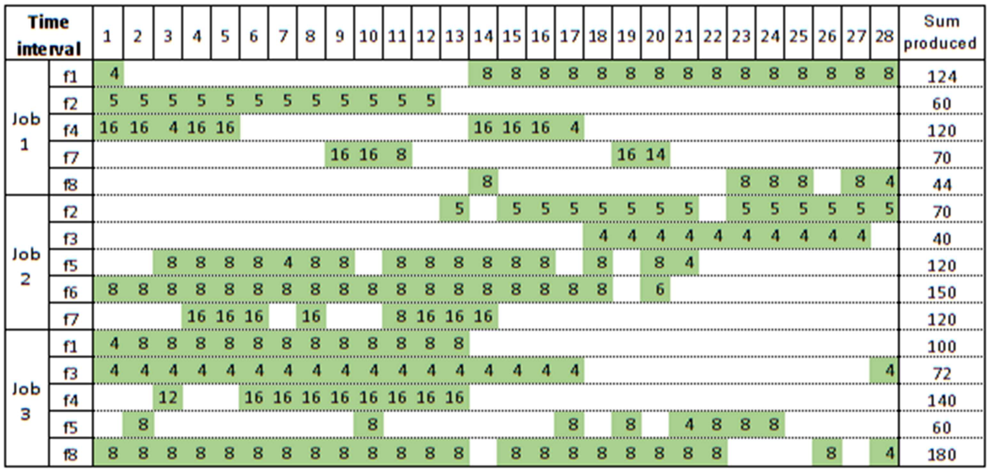
Table 5.4 Production schedule at fabrication shop 1



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced
Job 1	f1													8	8		8								2					26
	f2	5	5	5	5	5	5	5	5	5	5	5	5																	60
	f4																													0
	f7																													0
	f8						8	8	8	8	8	8	8	8				6	8	8										86
Job 2	f2													5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	80
	f3																	4	4	4	4	4	4	4	4	4	4	4	4	48
	f5																													0
	f6																													0
	f7																													0
Job 3	f1																													0
	f3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4													64
	f4																													0
	f5																													0
	f8																													0

(The number in each green cell is the quantity produced on that day)

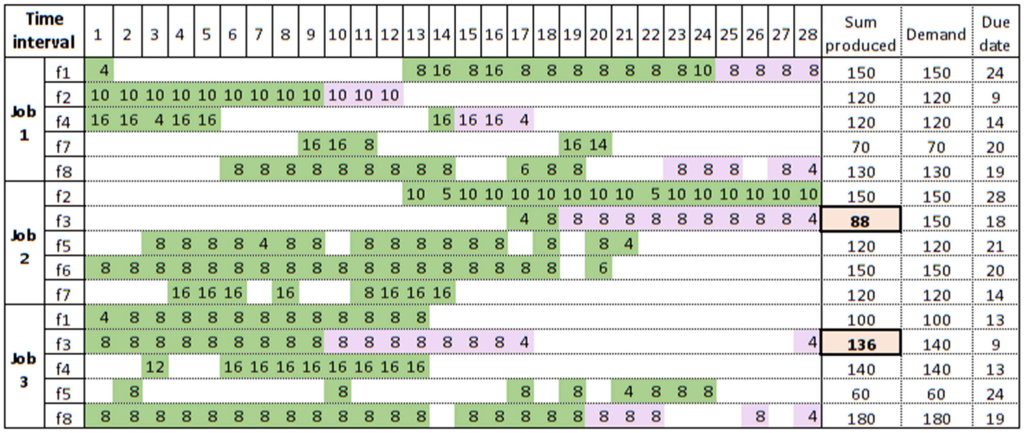
Table 5.5 Production schedule at fabrication shop 2



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced
Job 1	f1	4													8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	124
	f2	5	5	5	5	5	5	5	5	5	5	5	5																	60
	f4	16	16	4	16	16									16	16	16	4												120
	f7									16	16	8								16	14									70
	f8														8									8	8	8		8	4	44
Job 2	f2													5		5	5	5	5	5	5	5		5	5	5	5	5	5	70
	f3																		4	4	4	4	4	4	4	4	4	4		40
	f5			8	8	8	8	4	8	8		8	8	8	8	8	8		8		8	4								120
	f6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		6									150
	f7				16	16	16		16			8	16	16	16															120
Job 3	f1	4	8	8	8	8	8	8	8	8	8	8	8	8																100
	f3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4											4	72
	f4			12			16	16	16	16	16	16	16	16																140
	f5		8								8							8		8		4	8	8	8					60
	f8	8	8	8	8	8	8	8	8	8	8	8	8	8		8	8	8	8	8	8	8	8				8		4	180

(The number in each cell is the quantity produced on that day)

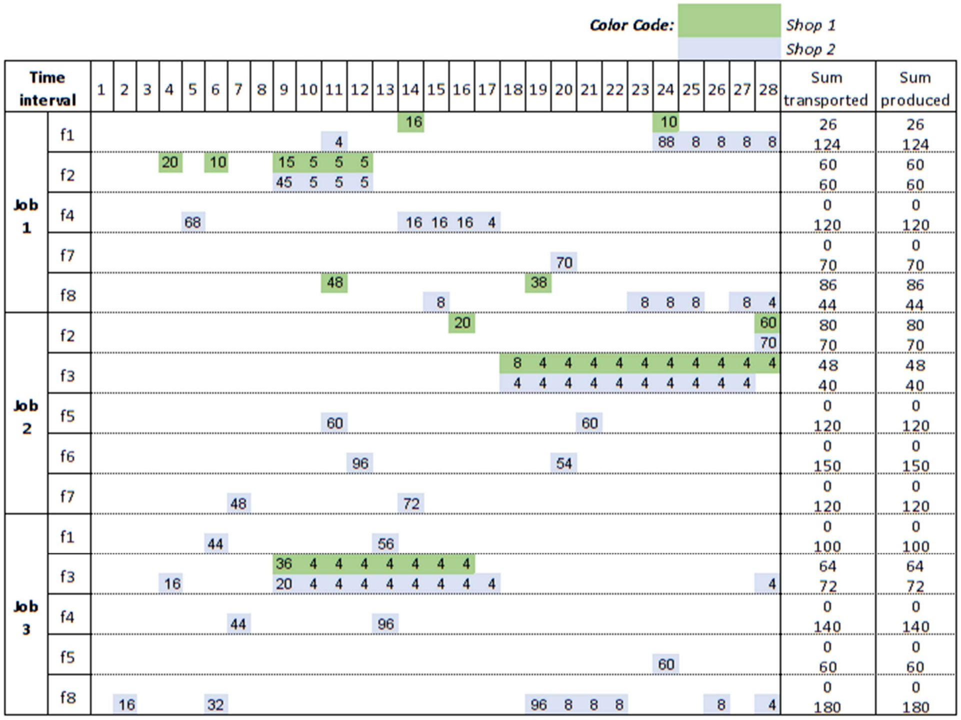
Table 5.6 Production schedule at fabrication shops 1 & 2



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced	Demand	Due date
Job 1	f1	4												8	16	8	16	8	8	8	8	8	8	8	10	8	8	8	8	150	150	24
	f2	10	10	10	10	10	10	10	10	10	10	10	10																	120	120	9
	f4	16	16	4	16	16									16	16	16	4												120	120	14
	f7									16	16	8								16	14									70	70	20
	f8						8	8	8	8	8	8	8	8	8			6	8	8				8	8	8		8	4	130	130	19
Job 2	f2													10	5	10	10	10	10	10	10	10	5	10	10	10	10	10	10	150	150	28
	f3																	4	8	8	8	8	8	8	8	8	8	8	4	**88**	150	18
	f5			8	8	8	8	4	8	8		8	8	8	8	8	8		8		8	4								120	120	21
	f6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		6									150	150	20
	f7				16	16	16		16			8	16	16	16															120	120	14
Job 3	f1	4	8	8	8	8	8	8	8	8	8	8	8	8																100	100	13
	f3	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	4											4	**136**	140	9
	f4			12			16	16	16	16	16	16	16	16																140	140	13
	f5		8								8							8		8		4	8	8	8					60	60	24
	f8	8	8	8	8	8	8	8	8	8	8	8	8	8		8	8	8	8	8	8	8	8				8		4	180	180	19

(The number in each cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy, the orange cells highlight unmet demand)

Table 5.7 Transportation schedule at fabrication shops 1 & 2

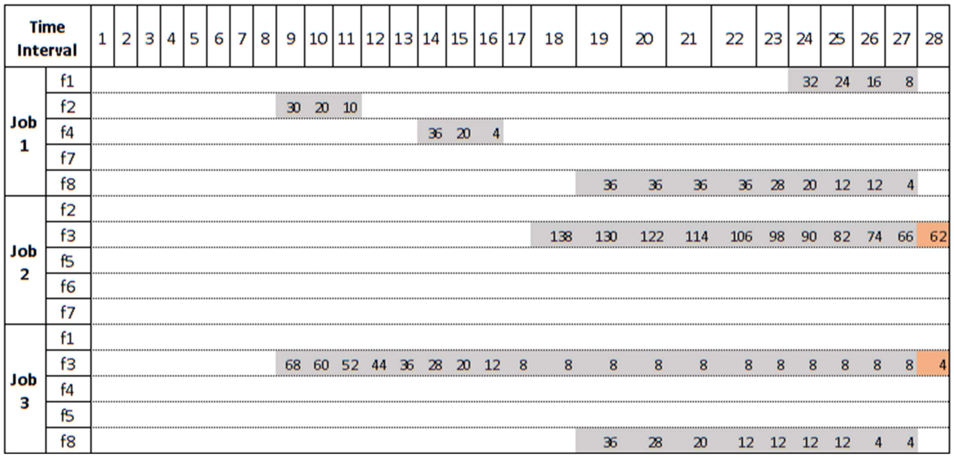


Color Code: 🟩 *Shop 1* 🟦 *Shop 2*

Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum transported	Sum produced
Job 1	f1														16										10					26	26
												4													88	8	8	8	8	124	124
	f2				20		10			15	5	5	5																	60	60
										45	5	5	5																	60	60
	f4																													0	0
						68									16	16	16	4												120	120
	f7																													0	0
																					70									70	70
	f8											48								38										86	86
																8								8	8	8		8	4	44	44
Job 2	f2																20												60	80	80
																													70	70	70
	f3																		8	4	4	4	4	4	4	4	4	4	4	48	48
																			4	4	4	4	4	4	4	4	4	4		40	40
	f5																													0	0
												60										60								120	120
	f6																													0	0
													96								54									150	150
	f7																													0	0
								48							72															120	120
Job 3	f1																													0	0
							44							56																100	100
	f3									36	4	4	4	4	4	4	4													64	64
					16					20	4	4	4	4	4	4	4	4											4	72	72
	f4																													0	0
								44						96																140	140
	f5																													0	0
																									60					60	60
	f8																													0	0
			16				32													96	8	8	8				8		4	180	180

(The number in each cell is the quantity delivered on that day)

Table 5.8 Tardiness quantity of different jobs



Time Interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Job 1	f1																								32	24	16	8	
	f2									30	20	10																	
	f4														36	20	4												
	f7																												
	f8																			36	36	36	36	28	20	12	12	4	
Job 2	f2																												
	f3																		138	130	122	114	106	98	90	82	74	66	62
	f5																												
	f6																												
	f7																												
Job 3	f1																												
	f3									68	60	52	44	36	28	20	12	8	8	8	8	8	8	8	8	8	8	8	4
	f4																												
	f5																												
	f8																			36	28	20	12	12	12	12	4	4	

(The number in each cell is the quantity of tardy job parts yet to be delivered, the number in the orange cell is the unmet demand quantity)

The example problem demonstrates a scenario when the supply chain cannot meet the demand quantities. Tables 5.4 to 5.6 reveal that the optimization model manages to produce as many job parts as possible before due dates in order to avoid delay costs. When the due dates have passed, the model continues to try to produce more job parts until meeting the demand quantities or hitting the end of the planning period. When it is not possible to meet the demand within the 28 days due to capacity constraints, the optimization model selects which job parts to produce in order to minimize the total cost.

The cost of not meeting the demand is set higher than the tardiness cost. This is reasonable since the objective function includes the processing cost and transportation cost for shortfall quantities which are the remaining quantities that the supply chain is incapable to produce before the end of the planning period (28 days). For the shortfall quantities, the unit processing costs are set at the maximum processing cost of these fabrication shops, and the transportation distance is set at the maximum transportation distance from the shops to construction job sites. When setting the cost for the shortfall quantities in this way, the optimization model will manage to produce as many quantities as possible to avoid higher costs, which can result from higher unit processing costs and higher transportation distance. Table 5.6 shows two instances when demand is not met. The first is for job part f3 of job 2 (demand quantity is 150, produced quantity is 88). The second is for job part f3 of job 3 (demand quantity is 140, produced quantity is 136). Processing time for each job part f3 is 4 hours/unit. Since the number of machine hours available for production each day is h= 16, each fabrication shop is only able to produce 4 job parts f3 per day. Tables 5.4 and 5.5 show that shop 1 and shop 2 are running at full capacity to produce 4 job parts f3 each day. Shop 1 produces 4 job parts f3 for job 3 each day from day 1 to day 16, and for job 2 from day 17 to day 28. Similarly, shop 2 produces 4 job parts f3 for job 3 from day 1 to day 17, 4 job parts f3 for job 2 from day 18 to day 27, and 4 job parts f3 for job 3 on day 28. Although these shops run at full capacity, they cannot meet the demand because the demand is higher than the shop's capacity.

Table 5.7 shows the transportation schedule generated from the optimization solution. As we can see from this table, the optimization model tries to deliver all produced job parts before due dates in order to avoid any delay costs. And the days to transport the job parts that are produced before the due dates could be any day after the day that the job parts are produced. It is understandable since no delay cost is applied before the due dates, so the optimization model has freedom to deliver the produced job parts at any time after the day that they are produced and before the due dates. After passing the due dates, the supply chain continues producing the remaining job parts and delivering all job parts right after production to avoid incurring additional tardiness costs. In case supply chain managers have more complicated rules for tardiness (e.g., one day late has a lower penalty than three days late) or other rules for truck loads and delivery schedules, I could set additional constraints in the optimization model to reflect that.

Table 5.8 presents the tardiness quantities of different jobs, which are the remaining quantities of job parts yet to be delivered after the due date. The tardiness quantities decrease every day as the system produces and delivers more job parts to construction sites. Almost all job parts are produced before the end of the planning period except for 62 units of job part f3 of job 2 and 4 units of job part f3 of job 3.

Sensitivity Analysis

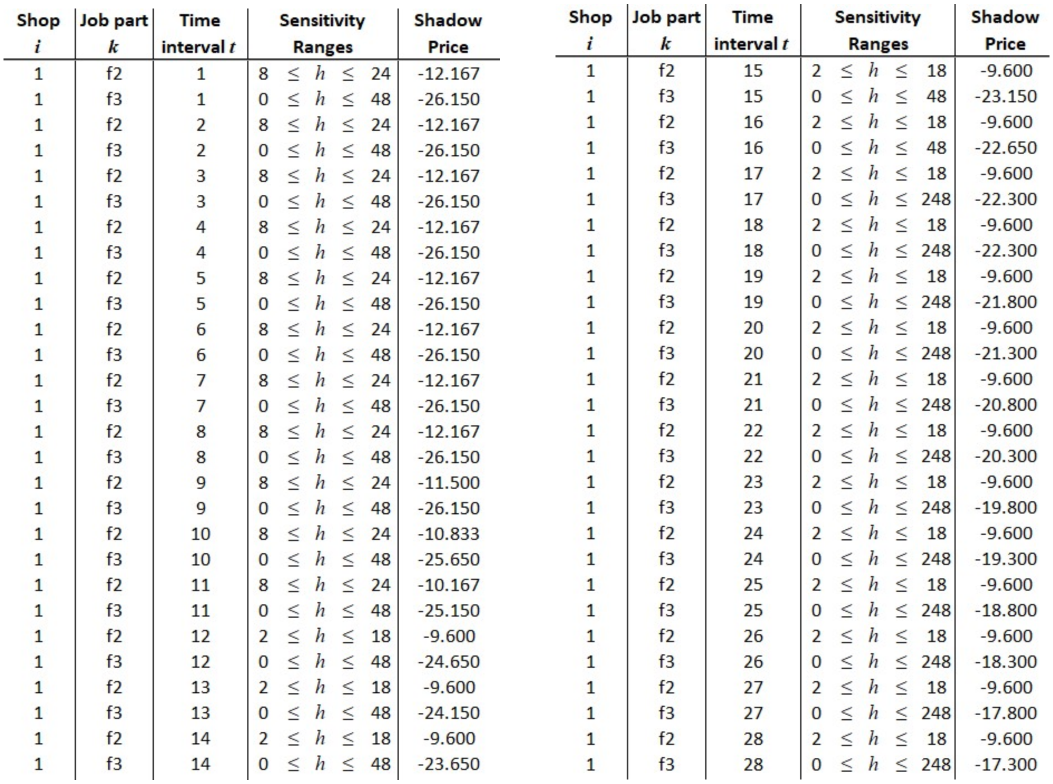
The example problem presents a case in which a fabrication supply chain cannot meet the demand in quantity and delivery time. If this happens in reality, it can damage the image of the business and potentially impact its position on the market. The presented optimization model can provide an insight about what supply chain managers could do to solve the problem. Since both shops are running at full capacity but could not meet the demand, the supply chain managers may consider boosting the capability of the shop by increasing the number of machines or by increasing the work hours. As we could see in Table 8, the delay happens for job parts f1, f2, f3, f4 and f8. Therefore, buying additional machines that process these job parts is a solution, but it may require a significant capital to purchase the machines. The supply chain managers could also consider increasing the work shifts from 8 to 10 hours or changing from 2 shifts to 3 shifts per day. However, the work shift increase could cause additional costs to operate additional shifts and higher unused capacity for the machines that are not utilized.

The impact of changes in shop capacities on the optimal cost could be investigated using sensitivity analysis. Sensitivity analysis studies how the optimal solution changes with different model parameters (Hillier & Lieberman, 2015). In this problem, since the work hours of machines indicate the shop capacity, I performed a sensitivity analysis on the constraint about machine availability. However, because the duality theory for integer programming (which forms the basis of sensibility analysis) is not fully developed (Guzelsoy & Ralphs, 2011; IBM, 2019), no sensitivity analysis model in CPLEX is currently available for integer programming. Therefore, in order to investigate the sensitivity of the developed integer programing model, I converted the integer programming model into a linear programming model by relaxing all variables from non-negative integer numbers to non-negative real numbers. After that, I performed the sensitivity analysis for the linear programming model. In the end, I tested the result of the linear programming model on the integer programming model.

Table 5.9 presents a sensitivity analysis result of the linear programming model for machine availability at shop 1 in the 28 days planning horizon. The shadow price in Table 5.9 indicates the decrease in total cost for an increase of one hour of h (from original value of 16) for the corresponding job part k at time interval t at shop 1, while h is within its maximum range. For example, the second row of Table 5.9 indicates that adding one hour to the machine that makes job part f3 in time interval 1 is more cost effective than adding one hour to the machine that makes job part f2 in time interval 1 as shown in row 1. Moreover, as time increases, the shadow price decreases indicating that adding time to machine availability early in the planning period is more effective than adding an hour late in the planning period. As a result, I chose to test the impact of changes on the machine availability for job part f3 at shop 1 on day 1.

Since it takes 4 hours for shop 1 to fabricate 1 unit of job part f3 (as in Table 5.2), an increase of at least 4 machine hours is needed to be able to increase 1 unit of production quantity for this job part. Therefore, I increased the available machine hours h for job part 3 in shop 1 at day 1 from 16 to 20 hours and ran a new optimization model. The new optimal cost is \$337,339, which is \$145 less than the optimal cost of the original model (\$377,484). This indicates that adding 4 machine hours to produce job part f3 in shop 1 at day 1 could reduce the optimal cost by \$145. Note that since the total machine hours spent for that job part in the entire planning period is almost the same for the new and the original model, this cost saving comes from the reduction in delay and the changes in job allocations. Based on this sensitivity analysis, the manager can make decisions in arranging resources in order to obtain further reduction in cost and delay.

Table 5.9 Sensitivity analysis of linear programming model for machine availability at shop 1



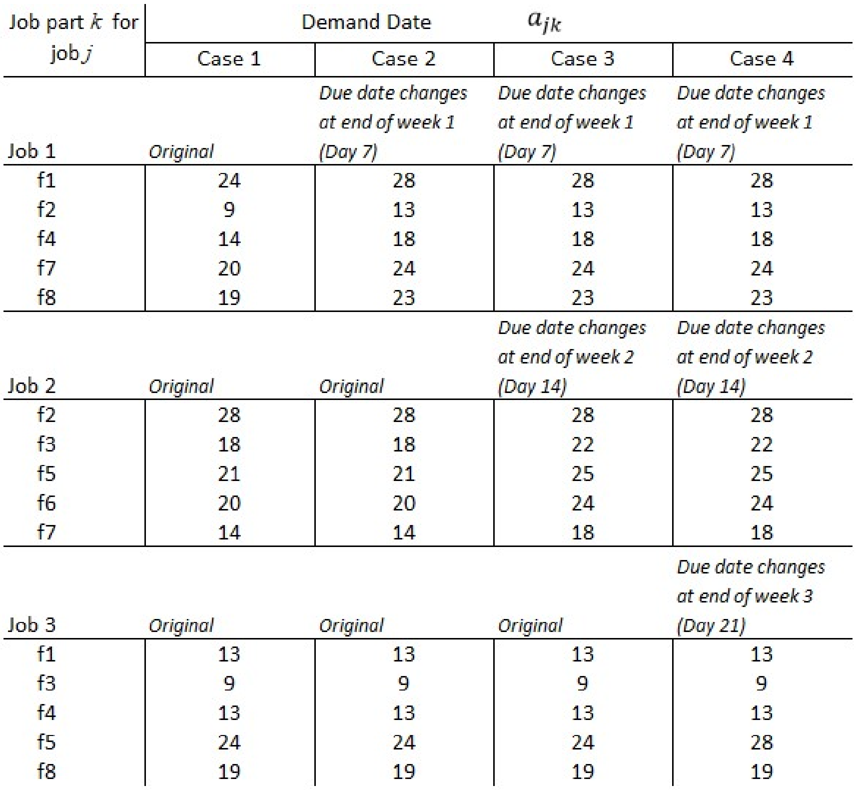
Shop i	Job part k	Time interval t	Sensitivity Ranges	Shadow Price
1	f2	1	$8 \le h \le 24$	-12.167
1	f3	1	$0 \le h \le 48$	-26.150
1	f2	2	$8 \le h \le 24$	-12.167
1	f3	2	$0 \le h \le 48$	-26.150
1	f2	3	$8 \le h \le 24$	-12.167
1	f3	3	$0 \le h \le 48$	-26.150
1	f2	4	$8 \le h \le 24$	-12.167
1	f3	4	$0 \le h \le 48$	-26.150
1	f2	5	$8 \le h \le 24$	-12.167
1	f3	5	$0 \le h \le 48$	-26.150
1	f2	6	$8 \le h \le 24$	-12.167
1	f3	6	$0 \le h \le 48$	-26.150
1	f2	7	$8 \le h \le 24$	-12.167
1	f3	7	$0 \le h \le 48$	-26.150
1	f2	8	$8 \le h \le 24$	-12.167
1	f3	8	$0 \le h \le 48$	-26.150
1	f2	9	$8 \le h \le 24$	-11.500
1	f3	9	$0 \le h \le 48$	-26.150
1	f2	10	$8 \le h \le 24$	-10.833
1	f3	10	$0 \le h \le 48$	-25.650
1	f2	11	$8 \le h \le 24$	-10.167
1	f3	11	$0 \le h \le 48$	-25.150
1	f2	12	$2 \le h \le 18$	-9.600
1	f3	12	$0 \le h \le 48$	-24.650
1	f2	13	$2 \le h \le 18$	-9.600
1	f3	13	$0 \le h \le 48$	-24.150
1	f2	14	$2 \le h \le 18$	-9.600
1	f3	14	$0 \le h \le 48$	-23.650
1	f2	15	$2 \le h \le 18$	-9.600
1	f3	15	$0 \le h \le 48$	-23.150
1	f2	16	$2 \le h \le 18$	-9.600
1	f3	16	$0 \le h \le 48$	-22.650
1	f2	17	$2 \le h \le 18$	-9.600
1	f3	17	$0 \le h \le 248$	-22.300
1	f2	18	$2 \le h \le 18$	-9.600
1	f3	18	$0 \le h \le 248$	-22.300
1	f2	19	$2 \le h \le 18$	-9.600
1	f3	19	$0 \le h \le 248$	-21.800
1	f2	20	$2 \le h \le 18$	-9.600
1	f3	20	$0 \le h \le 248$	-21.300
1	f2	21	$2 \le h \le 18$	-9.600
1	f3	21	$0 \le h \le 248$	-20.800
1	f2	22	$2 \le h \le 18$	-9.600
1	f3	22	$0 \le h \le 248$	-20.300
1	f2	23	$2 \le h \le 18$	-9.600
1	f3	23	$0 \le h \le 248$	-19.800
1	f2	24	$2 \le h \le 18$	-9.600
1	f3	24	$0 \le h \le 248$	-19.300
1	f2	25	$2 \le h \le 18$	-9.600
1	f3	25	$0 \le h \le 248$	-18.800
1	f2	26	$2 \le h \le 18$	-9.600
1	f3	26	$0 \le h \le 248$	-18.300
1	f2	27	$2 \le h \le 18$	-9.600
1	f3	27	$0 \le h \le 248$	-17.800
1	f2	28	$2 \le h \le 18$	-9.600
1	f3	28	$0 \le h \le 248$	-17.300

Impacts of the Variation in Due Date on the Optimal Value

To investigate the impact of the variations of due date on the cost performance of the supply chain, I created different due date scenarios and calculated the optimal costs at these scenarios. As delay is common in construction jobs, I tested the cases when the due date of some job parts is delayed in the middle of a production process.

The due dates for different scenarios are indicated in Table 5.10. Case 1 uses the original due dates as described in Table 5.3. Cases 2, 3, and 4 present scenarios where due dates change in the middle of the planning period. In Case 2, after the first week of the planning period, the due dates for all job parts in job 1 are extended by 4 days from those in Case 1. In Case 3, after the second week of the planning period, the due dates for all job parts in job 2 are extended by 4 days from those in Case 2 except for f2 because its due date is already at the end of the planning period. In Case 4, after the third week of the planning period, the due dates for job part f5 in job 3 is extended by 4 days from those in Case 3. The due dates for job parts f1, f3, f4 and f8 are not extended because the original due dates have already passed.

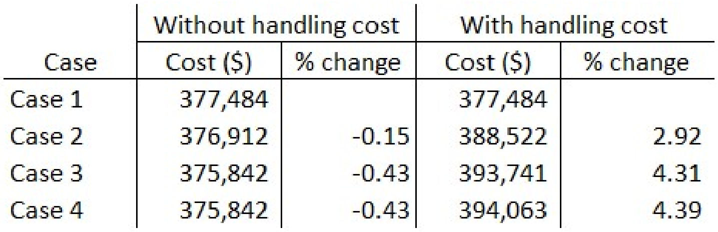
Table 5.10 Different scenarios about due dates



Job part k for job j	Demand Date a_{jk}			
	Case 1	Case 2	Case 3	Case 4
Job 1	*Original*	*Due date changes at end of week 1 (Day 7)*	*Due date changes at end of week 1 (Day 7)*	*Due date changes at end of week 1 (Day 7)*
f1	24	28	28	28
f2	9	13	13	13
f4	14	18	18	18
f7	20	24	24	24
f8	19	23	23	23
Job 2	*Original*	*Original*	*Due date changes at end of week 2 (Day 14)*	*Due date changes at end of week 2 (Day 14)*
f2	28	28	28	28
f3	18	18	22	22
f5	21	21	25	25
f6	20	20	24	24
f7	14	14	18	18
Job 3	*Original*	*Original*	*Original*	*Due date changes at end of week 3 (Day 21)*
f1	13	13	13	13
f3	9	9	9	9
f4	13	13	13	13
f5	24	24	24	28
f8	19	19	19	19

Since postponing work in the middle of the production process requires the rearrangement of materials, machines, tools and personal, a handling cost should be included. Two cost functions are proposed: the first cost function is the original one that does not include a handling cost, while the second cost function includes a handling cost. The handling cost is estimated as 15% of the average cost to produce the job parts that are postponed. Figure 5.2 shows the optimal cost for each case when the handling cost is and is not included. As the due dates in these cases shift to later days when going from Case 1 to Case 4, we might expect that the supply chain becomes more flexible in scheduling the production process, leading to a reduced cost. Indeed, the optimal cost decreases when moving from Case 1 to Case 4 as expected. However, this first cost function does not include a handling cost. When a handling cost is included in the second cost function then the total cost increases for Cases 2, 3, and 4. Table 5.11 and Figure 5.2 present the optimal costs for the four cases with postponed jobs, with and without a handling cost. As shown in Table 5.11, the optimal cost for Case 2 using the first cost function without handling cost results in a decrease of 0.15% from Case 1 and using the second function with handling cost results in an increase of 2.92% from Case 1. Similarly, Case 3 and 4 decrease the total cost when ignoring the handling cost and increase the total cost when the handling cost is included. This shows that the cost of handling changes in the middle of the production process can significantly impact the cost of the supply chain.

Table 5.11 Optimal cost for different cases with postponed jobs



	Without handling cost		With handling cost	
Case	Cost ($)	% change	Cost ($)	% change
Case 1	377,484		377,484	
Case 2	376,912	-0.15	388,522	2.92
Case 3	375,842	-0.43	393,741	4.31
Case 4	375,842	-0.43	394,063	4.39

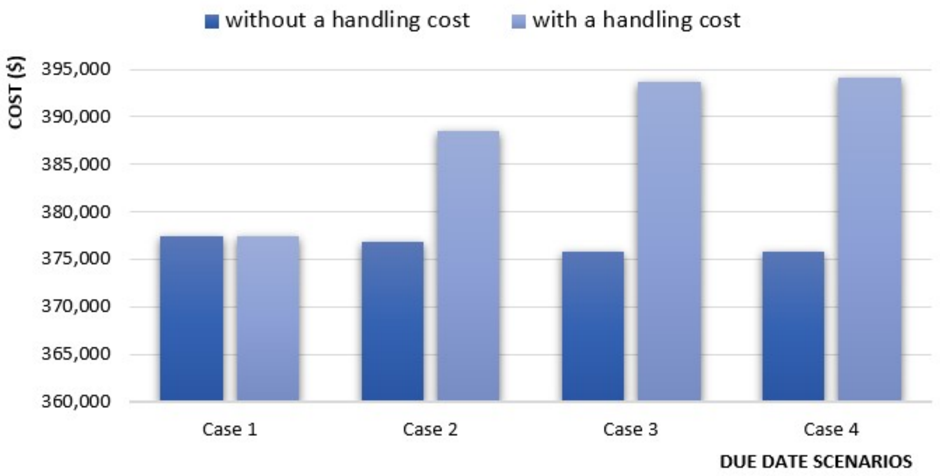


Figure 5.2 Optimal costs for different cases with postponed jobs, contrasting cost functions with and without handling costs

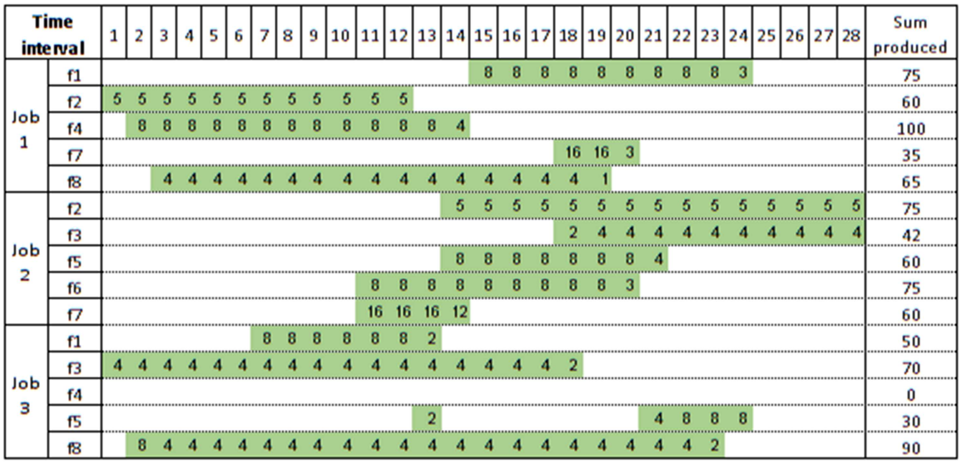
This analysis indicates that postponing the work in the middle of the planning period could make the supply chain managers more flexible in scheduling their production process and could lead to a better chance to reduce the cost. However, the increase in flexibility when postponing jobs only happens if no work is needed to handle the changes. In reality, postponing the work in the middle of the production period usually causes a handling cost to change materials, machines and workers, leading to an increase in the total cost. Any changes in timing demands could disrupt the schedule and affect any related work. Such changes could carry over into another planning period and may require the rearrangement of the production process of the supply chain. A robust optimization model that considers the impact of any changes along different planning periods would be helpful for prefabrication supply chain managers in managing their production systems and should be investigated in future research.

Scheduling the Production Process Using the Early Due Date (EDD) Method

To verify the effectiveness of the optimization model, I have developed a production schedule for the supply chains using the Early Due Date (EDD) method (Krajewski, Ritzman & Malhotra, 2010). This method assigns jobs by giving the highest priority to the jobs with the earliest due date. This method focuses mainly on reducing the delay and does not consider reducing the cost. When applying the EDD method, I assumed that 50% of the jobs are assigned to shop 1 and 50%

are assigned to shop 2. Tables 5.12 to 5.14 present the shop production schedule that were developed using the EDD method.

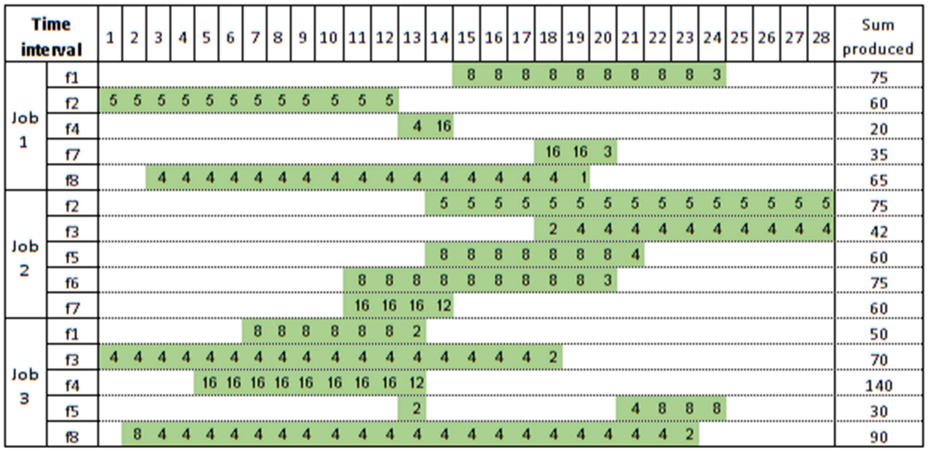
Table 5.12 Production schedule based on Early Due Date method for shop 1



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced
Job 1	f1															8	8	8	8	8	8	8	8	8	3					75
	f2	5	5	5	5	5	5	5	5	5	5	5	5																	60
	f4		8	8	8	8	8	8	8	8	8	8	8	8	4															100
	f7																		16	16	3									35
	f8			4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	1										65
Job 2	f2														5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	75
	f3																		2	4	4	4	4	4	4	4	4	4	4	42
	f5														8	8	8	8	8	8	8	4								60
	f6											8	8	8	8	8	8	8	8	8	3									75
	f7											16	16	16	12															60
Job 3	f1							8	8	8	8	8	8	2																50
	f3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2											70
	f4																													0
	f5													2								4	8	8	8					30
	f8		8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2						90

(The number in each cell is the quantity produced on that day)

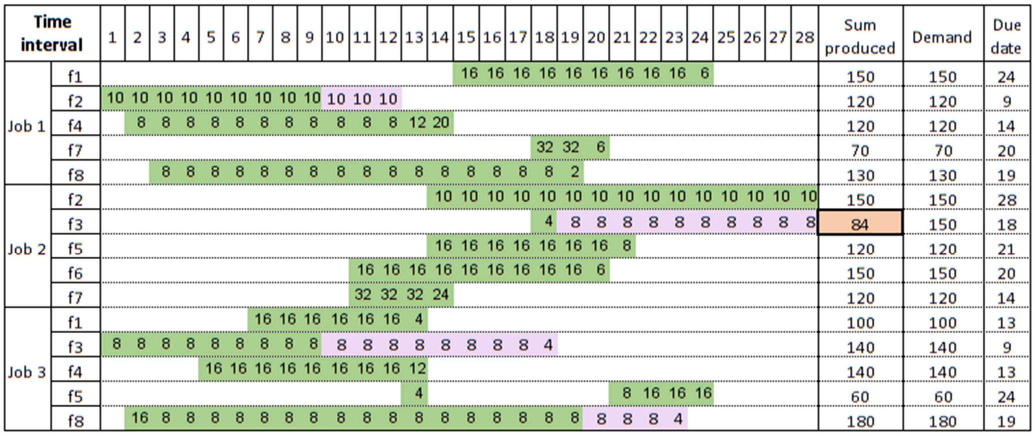
Table 5.13 Production schedule based on Early Due Date (EDD) method for shop 2



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced
Job 1	f1															8	8	8	8	8	8	8	8	8	3					75
	f2	5	5	5	5	5	5	5	5	5	5	5	5																	60
	f4													4	16															20
	f7																		16	16	3									35
	f8			4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	1										65
Job 2	f2														5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	75
	f3																		2	4	4	4	4	4	4	4	4	4	4	42
	f5														8	8	8	8	8	8	8	4								60
	f6											8	8	8	8	8	8	8	8	8	3									75
	f7											16	16	16	12															60
Job 3	f1							8	8	8	8	8	8	2																50
	f3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2											70
	f4					16	16	16	16	16	16	16	16	12																140
	f5													2								4	8	8	8					30
	f8		8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2						90

(The number in each cell is the quantity produced on that day)

Table 5.14 Production schedule based on Early Due Date (EDD) method for shops 1 & 2



Time interval		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced	Demand	Due date
Job 1	f1															16	16	16	16	16	16	16	16	16	6					150	150	24
	f2	10	10	10	10	10	10	10	10	10	10	10	10																	120	120	9
	f4		8	8	8	8	8	8	8	8	8	8	8	12	20															120	120	14
	f7																		32	32	6									70	70	20
	f8			8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	2										130	130	19
Job 2	f2														10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	150	150	28
	f3																		4	8	8	8	8	8	8	8	8	8	8	84	150	18
	f5														16	16	16	16	16	16	16	8								120	120	21
	f6											16	16	16	16	16	16	16	16	16	6									150	150	20
	f7											32	32	32	24															120	120	14
Job 3	f1							16	16	16	16	16	16	4																100	100	13
	f3	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	4											140	140	9
	f4					16	16	16	16	16	16	16	16	12																140	140	13
	f5													4								8	16	16	16					60	60	24
	f8		16	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	4						180	180	19

(The number in each green cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy, the orange cells highlight unmet demand)

The total cost obtained when using the EDD method is $387,020, which is 2.5% higher than the total cost obtained when using the optimization model ($377,484). Regarding the cost components of the total cost, the production cost obtained from the EDD method is higher than that obtained when using the optimization model, while the delay cost in the EDD method is lower than that obtained when using the optimization model. I consider this result to be reasonable since the optimization model attempts to reduce the total cost of the supply chain by doing a trade-off between different factors such as the production cost, transportation cost, and delay cost. However, the EDD method only focuses on reducing delay without considering other factors.

5.6 SUMMARY

This chapter presents research on the application of an optimization model to job allocations in prefabrication construction supply chains with multiple fabrication shops. It reports the results of a preliminary industry survey used to assess the need for an optimization model for prefabrication construction supply chains. This chapter also discusses the computational results of an example problem for a supply chain with 2 fabrication shops and 3 construction projects. The results show that the model could assist supply chain managers by finding the best possible solutions in allocating jobs and creating production schedules. The model generates an optimal solution with 2.5% cost reduction, compared to the solution generated by the traditional Early

Due Date (EDD) method. Through a sensitivity analysis, the model helps identify the parameters sensitive to the changes, such as the availability of machine hours at certain time intervals and quantifies the impact of these parameters on the supply chain performance. Moreover, by analyzing the impact of due date variations on the optimal results in an example problem, it shows that postponing due dates in the middle of a production process could reduce the total cost by 0.49% because of the improved flexibility. However, postponing the due date could incur a handling cost that makes the total cost jump by 4.39%, well surpassing the savings achieved by increasing flexibility. Therefore, contractors are recommended to take into account the impact of their demand variations on prefabrication supply chain performance. In addition, construction prefabricators should keep track of operational data, such as productivity rates and associated costs for management purposes and for implementing optimization and other advanced technologies.

Chapter 6. PRODUCTION PLANNING OF CP&M SUPPLY CHAIN CONSIDERING VARIABLE DELIVERY TIMES

Overview: As prefabrication and modularization are widely used in the construction industry, efficiencies of the operation of prefabrication supply chains result in benefits for construction projects. While the variable delivery time of construction schedules impacts the operation efficiencies of prefabrication supply chains, few studies have investigated this problem by addressing uncertainties in the prefabrication schedules. This study aims to fill this gap by investigating the impact of uncertainty regarding required delivery times on prefabrication supply chains with multiple shops. An industry survey presented in Chapter 4 reveals that it is common for construction projects to change the required delivery time of prefabricated products. This chapter presents a multi-objective stochastic programming model that facilitates the production planning of prefabrication supply chains with multiple fabrication shops considering variable delivery times, also, computational results for an example problem with three fabrication shops, ten construction projects and fifteen job parts. The model allows fabricators to develop a robust set of optimal schedules that are flexible in balancing cost and time reduction objectives.

6.1 BACKGROUND

Previous studies have recognized that uncertainty is an enemy of workflows (Koskela, 2000; Brodetskala et al., 2013; Ma and Sacks, 2016). However, it is unavoidable in many economic sectors, especially in the construction industry. Gidado (1996) claims that the increase in complexity of construction supply chains is a result of uncertainties involving resources, environments, and the operational interdependence among tasks. Howell et al. (1993) discuss various types of uncertainties in construction projects such as project objective uncertainty, project mean and method uncertainty, workflow uncertainty, labor and resource uncertainty. According to Howell et al., uncertainties may cause the delay or postpone of works from schedule. Laufer and Cohenca (1990) investigate the impact of uncertainties on planning by examining the variables such as subcontractor quantity, objective rigidity, design completion percentage, weather predictability, and labor availability. Their study shows that planning outcomes are significantly impacted when production contexts change from simple to complex and uncertain. They also indicate that the design completion percentage, the past construction experience of contractors, labor availability, weather predictability and the attitudes toward planning are amongst factors that strongly influence planning outcomes. Because of the prevalence of uncertainties in the construction industry, Ballard and Howell (1998) suggest using a shielding process to protect construction projects from uncertainties and improve the reliability of workflows.

Uncertainty can impact various construction supply chains. Construction prefabrication and modularization (CP&M) supply chains are not an exception. Since the demand of each construction project is unstable or unpredictable, it poses a challenge for suppliers to respond to the changes. Moreover, the impact of uncertainty can be exaggerated with the wide application of pull system in construction prefabrication and modularization (Tommelein, 1998; Kim et al., 2016). Pull system allows contractors to trigger their production process based on the system status such as capacities and customer demands to minimize inventory (Hopp, 2008; Chopra and Meindl, 2014). While pull system helps reduce inventory, this reduction could make the prefabrication supply chains less flexible and fall into material shortage when facing with certain demand changes. Demand uncertainty of construction projects negatively affects the performance of prefabrication supply chains. Nonetheless, few studies have incorporated the demand uncertainty of construction schedules into the production planning of prefabrication supply chains. This study proposes to bridge this gap by investing the impact of demand uncertainty on the production of prefabrication supply chains with multiple fabrication shops.

The study included in this chapter extends the study addressed in Chapter 5 regarding the production planning of CP&M supply chain with multiple fabrication shops by incorporating uncertainty and considering tradeoffs between cost and delay. The previous survey carried out during 2017 in the Pacific Northwest reveals that many prefabrication companies are operating multiple fabrication shops at different regional locations to reduce cost and meet customer demands, but few quantitative models are available to facilitate the job allocations problems. Planning and scheduling supply chain networks with multiple production stages and facilities have been addressed in previous studies. However, little study in prefabrication construction has addressed this problem. Unlike manufacturing sectors, construction projects are unique and job-specific, making it difficult to apply optimization models which are available in other industries. While several studies have addressed optimization problems in job shop schedule, inventory and cost for individual construction sites or individual fabrication shops, few have paid attention to the coordination between multiple fabrication shops and the optimization of supply chain planning and scheduling. Therefore, this study aims to fill the knowledge gap in this area and to propose a model to support prefabrication supply chain with multiple fabrication shops.

Demand uncertainty regarding required delivery time of prefabricated materials can be analyzed using stochastic programming. The literature indicates that many studies have successfully applied stochastic programing to investigate uncertainties. Barbarosoğlu and Arda (2004) propose a two-stage stochastic programing model for the transportation of the first aid commodities such as medicine, food, clothing, machinery to areas affected by disasters during emergency response. Darby-Dowman et al. (2000) propose a two-stage stochastic programing with recourse for the determination of optimal planting plans for a vegetable crop. Donadee and Ilic (2014) apply stochastic programing to optimize the charging and frequency regulation capacity bids of an electric vehicle in an electric grid environment. Marufuzzaman et al. (2014) propose a two-stage location-transportation stochastic programming model which incorporates carbon emission considerations and uncertainties to supports the design and management of biodiesel supply chains. Sakawa et al. (2014) develop a two-level linear programming problem with random variables in constraints. Swati et al. (2016) use stochastic programing to optimize cable replacement problems. Mitra et al. (2016) propose a cross-decomposition algorithm combining Benders and Lagrangian decompositions for investment planning problems using a two-stage programming with recourse model. Topcu et al. (2008) develop a multi-period stochastic programming model with recourse to identify the multi-period allocation of storage space in remanufacturing facilities using the pull system. The Xu et al. study (2015) investigate the impact of scenario tree reduction on the performance of stochastic model for hydro operations and proposed a method to identify the optimal level of the scenario tree reduction method. Zanjani et al. (2010) study a multi-stage stochastic program for the production planning of a multi-period, multi-product system with uncertainties in demand and yield. The demand was modeled through a scenario tree with dynamic stochastic processes (Zanjani et al., 2010). Zhou et al. (2013) propose a two-stage stochastic programing model for the design of distributed energy systems. Li and Zabinsky (2011) use stochastic programming with recourse to incorporate the uncertainty in supplier capacity and demand in a supplier selection problem. Mete and Zabinsky (2010) use stochastic programming to aid in storage and distribution of medical supplies in the event of an earthquake. Zhu and Mostafavi (2015) present a multi-node multi-link and dynamic network analysis framework to analyze the impact of uncertainties on construction project performance.

This research addresses above needs and knowledge gaps by analyzing the impact of uncertainty into the production planning of construction prefabrication and modularization (CP&M) supply chain with multiple fabrication shops and studying the tradeoffs between minimizing cost and delay objectives. The following sections introduce the research method, develop an optimization model, discuss an example problem and present research findings.

6.2 RESEARCH METHOD

Recognize the impact of uncertainty on supply chain performance, this study involves in developing a multi-objective stochastic programming optimization model for CP&M supply chain, specifically for the one with multiple fabrication shops. In this CP&M supply chain, the coordination across the network of different shops must account for transportation distances, shop capacities, inventory, time and cost. The jobs herein correspond to the construction projects that need prefabricated materials. A job may include a set of job parts with varying delivery times. For certain fabrication and module assemblies such as rebar, façade units or MEP components, since materials are fabricated and assembled within a few days before delivery dates, storage area for both raw materials and fabricated/assembled materials is not a concern. However, other construction products may require longer production time such as the curing time for precast units, or when multiple trades are needed to fabricate the modules, storage areas can be a factor influencing cost and schedule. The stochastic programming is created to incorporate the impacts of uncertainty via different scenarios regarding required delivery dates. The stochastic programming allows to evaluate the impact of different realizations of uncertainty on the cost and schedule of prefabrication supply chains, thereby gaining insight about the relationship between uncertainty and supply chain performance.

The allocations of jobs between fabrication shops in this supply chain is presented in Figure 6.1, and a variation in required delivery times is shown in Table 6.1. Figure 6.1 and Table 6.1 also present the example problem that is introduced later in this chapter for a CP&M supply chain with three shops and ten construction projects.

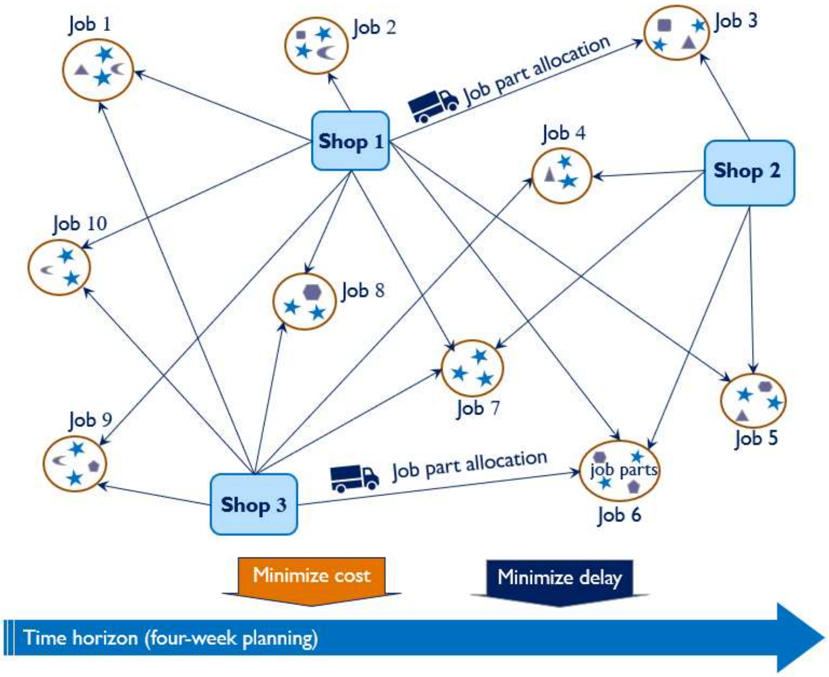
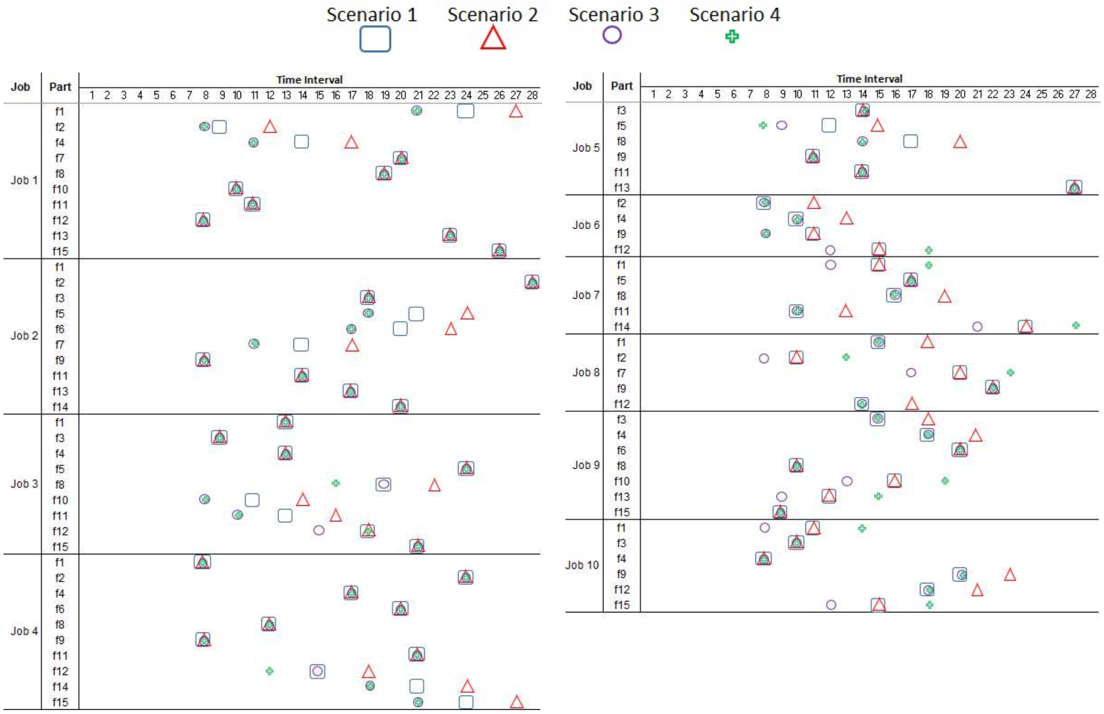


Figure 6.1 Job allocation of prefabrication supply chain with multiple fabrication shops

Table 6.1 Required delivery times for job parts with four scenarios



In Table 6.1, Scenario 1 indicates the original due dates (or required delivery times) that have been agreed between the fabricator and construction projects. In Scenario 2, the due dates of some job parts in Scenario 1 are postponed for three days. In Scenario 3, the due dates of some job parts in Scenario 1 are moved back three days earlier. In Scenario 4, the due dates of some job parts in Scenario 1 are postponed for three days for job 1 to job 5 and are moved back for three days for job 6 to job 10. Table 6.5 also provides the information about required delivery times for the four scenarios.

The uncertainty of the required delivery time is determined based on relevant data from the literature and from my survey. Ballard et al. (1996) indicated that percent plan complete (the percentage of the works completed as planned) of a case study project included in their study increased from 65% to 85% after improving the reliability of job assignments. Kim (2019) investigated percent constraint removal (the number of works assigned in the weekly work plan compared to the number of works planned in n-week look ahead plan) based on 53 construction projects in Korea. The average percent constraint removal (PCR) identified from his study is 83%. This means that around 17% of works planned in the look ahead plan do not happen in the weekly week plan. However, the PCR of the case study projects in Kim's study is higher compared with the normal cases since these construction projects have implemented Last Planner System for several years so that job assignments in these projects have good quality, leading to high PCR values. On the other hand, a fabrication contractor participated in my survey revealed that he tracked the change in the required delivery time from construction projects and found that changes in the required delivery time happen in 30% of works. As a result, I assumed that 30%-40% of the jobs in this example problem change the required delivery time.

Choosing a shop with smaller transportation distance or production cost can reduce transportation cost. However, in case the nearest shop does not have enough capacity, the job will be assigned to another shop. As a result, the fabricator can reduce delay and increase resource utilization. To provide supply chain managers with a clear picture about the tradeoffs between different objectives such as minimizing cost and minimizing delay, an efficient frontier with Pareto-optimal solutions is developed. Resources are allocated in the most efficient manner in a Pareto-optimal solution, in which one objective in the solution cannot be improved without making other objectives worse (Rardin 1998). In this research, the Pareto frontier indicates the relationship between total cost and total delay. The presentation of the Pareto-optimal solutions with the efficient frontier supports decision-makers in evaluating the tradeoffs and balance different objectives.

To demonstrate and verify the performance of the optimization models, an example problem is developed with three fabrication shops, ten jobs and fifteen job parts in a 28-day planning horizon. Each job corresponds to a construction project that demands for different prefabricated components (job parts). I employ DOCPLEX, an IBM Decision Optimization CPLEX Modeling for Python (DOCPLEX version 2.9.141, 2019) to solve the model. I use Python (version 3.6, 2018) as an application programming interface (API) to call DOCPLEX, read data, write the problem and present the computational results. The input data for the optimization model is written in a relational database management system named SQLite (version 3.10.1, 2016). The use of Python, DOCPLEX and SQLite allows to streamline the creation of input data and the analysis of computational results. The input data is the information about various parameters such as job demands, processing time, processing cost, availability of machines, scenarios about required delivery time. The computational results are the decisions about times to fabricate job parts, the fabrication shop that the job parts are assigned to, and the machine used for the job parts. The computational results also include the outcome of the optimization objectives such as the total cost, and total delay time.

Finally, the computational results generated from above problem are analyzed to evaluate the performance of the optimization models, study the tradeoffs between cost and time, recognize potential applications of the optimization models and identify improvement opportunities.

6.3 MATHEMATICAL MODEL

The optimization model incorporates both multi-objective and stochastic programming. Two objectives are addressed including minimizing total cost and minimizing total delay. A two-stage stochastic program is developed to reflect delivery time uncertainty with different scenarios. The first stage is to determine the production plan for the first week in the plan period, the second stage is to determine the production plan for the remaining three weeks of the planning period which are subject to the uncertainty in required delivery time. The assumptions used in the model are:

1. The prefabrication supply chain includes many fabrication shops situated at different locations.
2. The supply chain provides fabricated materials for many construction projects.
3. Jobs are allocated between these fabrication shops based on processing cost, transportation distance and shop capacity.
4. Each job is a construction project that requires different prefabricated items (or job parts).
5. Each fabrication shop has all machines that can process all types of job parts.
6. Each type of job part is processed by a single machine.
7. Each fabrication shop has one machine for each type of job part.
8. Each fabrication shop has an unlimited inventory and storage capacity.
9. The supply chain has unlimited labor capacity to do all types of job parts.
10. The supply chain does not allocate inventory amongst the shops.

11. The supply chain has an unlimited transportation capacity, all prefabricated items could be transported to the job site within the day that they are produced.

The optimization model includes sets, variables and parameters as follows:

Sets

I: Set of fabrication shops.

J: Set of jobs.

K: Set of job parts.

T: Set of time intervals (days) in the time horizon.

SC: Set of scenarios about required delivery time.

Variables

$\tilde{x}_{ijkt}$: Quantity (in unit) of job part k in job j produced at fabrication shop i in time interval t given for $i \in I, k \in K, j \in J, t \in \{1, \dots, 7\}$

$\tilde{y}_{ijkt}$: The quantity of job part k transported from the fabrication shop i to the construction site of job j at time t given for $i \in I, k \in K, j \in J, t \in \{1, \dots, 7\}$

$\tilde{v}_{jkt}$: The quantity (in unit) of job part k that is tardy (have are not arrived) at job j at the end of time interval t for $i \in I, k \in K, t \in \{1, \dots, 7\}$.

$x_{ijkt}(\xi)$: Quantity (in unit) of job part k in job j produced at fabrication shop i in time interval t given the scenario ξ for $i \in I, k \in K, j \in J, t \in \{8, \dots, T\}$.

$y_{ijkt}(\xi)$: The quantity of job part k transported from the fabrication shop i to the construction site of job j at time t given the scenario ξ for $i \in I, k \in K, j \in J, t \in \{8, \dots, T\}$.

$v_{jkt}(\xi)$: The quantity (in unit) of job part k that is tardy (have are not arrived) at job j at the end of time interval t given the scenario ξ for $i \in I, k \in K, t \in \{8, \dots, T\}$.

Parameters

D_{jk}: Demand (in unit) for job part k in job j for $k \in K, j \in J$.

a_{jk}: The due date of job part k of project j at the first week of the planning period ($t \in \{1, \dots, 7\}$) for $k \in K, j \in J$.

$a_{jk}(\xi)$: The due date of job part k of project j given the scenario ξ for $k \in K, j \in J$ provided that the due date at the first week of the planning period is fixed.

$p(\xi)$: The probability of scenario ξ for $\xi \in SC$.

h_{ik}: Processing time (in hour) for job part k at fabrication shop i for $i \ \in I, \ k \ \in K$.

$\tilde{h}$: Number of machine hours per day available for production.

t^{end}: The last day in the considered time horizon

c_{ik}^{p}: The cost to process a unit of job part k at fabrication shop i for $i \ \in I, \ k \ \in K$.

$c_{k}^{p_{tardy}}$: The estimated cost to process a unit of job part k that is still delayed at the end of the time horizon for $k \ \in K$.

c_{k}^{m}: The cost to transport one unit of job part k for one km transportation distance for $k \ \in K$.

d_{ij}: Transportation distance (in km) from fabrication shop i to the construction site of job j for $i \ \in I, \ j \ \in J$.

d_{j}^{tardy} : Estimated transportation distance (in km) from a fabrication shop to the construction site of job j for the job parts that are still tardy at the end of the time horizon for $j \ \in J$.

w_{jk}: The tardiness (delay) cost per unit per day for an order of job part k of project j that is delayed $j \ \in J, \ k \ \in K$.

The two-stage stochastic programming model with two objectives is formulated as follows:

- Minimize total cost: $C_1 + C_2$ where:

$$C_1 = \sum_{t\in\{1,\ldots,7\}} \sum_{k\in K} \sum_{j\in J} \sum_{i\in I} c_{ik}^{p} \ \tilde{x}_{ijkt} + \sum_{t\in\{1,\ldots,7\}} \sum_{k\in K} \sum_{j\in J} \sum_{i\in I} c_{k}^{m} \ \tilde{y}_{ijkt} d_{ij}$$
$$+ \sum_{t\in\{1,\ldots,7\}} \sum_{k\in K} \sum_{j\in J} w_{jk} \ \tilde{v}_{jkt}$$

$$C_2 = \sum_{t\in\{8,\dots,T\}} \sum_{k\in K} \sum_{j\in J} \sum_{i\in I} \sum_{\xi\in SC} c_{ik}^{p}\, x_{ijkt}(\xi)\ \mathrm{p}(\xi)$$

$$+ \sum_{t\in\{8,\dots,T\}} \sum_{k\in K} \sum_{j\in J} \sum_{i\in I} \sum_{\xi\in SC} c_{k}^{m}\, y_{ijkt}(\xi)\, p(\xi)$$

$$+ \sum_{t\in\{8,\dots,T\}} \sum_{k\in K} \sum_{j\in J} \sum_{\xi\in SC} w_{jk} v_{jkt}(\xi)\, p(\xi)$$

$$+ \sum_{j\in J} \sum_{k\in K} \sum_{\xi\in SC} c_{k}^{p_{tardy}}\ v_{jkt^{end}}(\xi)\, p(\xi)$$

$$+ \sum_{j\in J} \sum_{k\in K} \sum_{\xi\in SC} c_{k}^{m} v_{jk\ end}(\xi) d_{j}^{tardy} p(\xi)$$

- Minimize total delay: $L_1 + L_2$ where:

$$L_1 = \sum_{t\in\{1,\dots,7\}} \sum_{k\in K} \sum_{j\in J} \tilde{v}_{jkt}$$

$$L_2 = \sum_{t\in\{8,\dots,T\}} \sum_{k\in K} \sum_{j\in J} \sum_{\xi\in SC} v_{jkt}(\xi)\, p(\xi)$$

Subject to the constraint in the availability of machine at fabrication shops:

$$\sum_{j\in J} h_{ik} x_{ijkt} \le \tilde{h} \quad i \in I \quad t \in \{1,\dots,7\} \quad k \in K$$

$$\sum_{j\in J} h_{ik} x_{ijkt}(\xi) \le \tilde{h} \quad i \in I \quad t \in \{8,\dots,T\} \quad k \in K \quad \xi \in SC$$

Subject to the constraint in the tardy job:

$$\sum_{\tau} \sum_{i\in I} \tilde{y}_{ijk\tau} + \tilde{v}_{jkt} = D_{jk} \quad t \in \{1,\dots,7\} \quad t \ge a_{jk} \quad j \in J \quad k \in K$$

$$\sum_{\tau} \sum_{i\in I} y_{ijk\tau}(\xi) + v_{jkt}(\xi) = D_{jk} \quad t \in \{8,\dots,T\} \quad t \ge a_{jk}(\xi) \quad j \in J \quad k \in K \quad \xi \in SC$$

Subject to the constraint in the total transportation quantity:

$$\sum_{t\in\{1,\dots,7\}}\sum_{i\in I}\tilde{y}_{ijkt} + \sum_{t\in\{8,\dots,T\}}\sum_{i\in I}y_{ijkt}(\xi) = \sum_{t\in\{1,\dots,7\}}\sum_{i\in I}\tilde{x}_{jkt} + \sum_{t\in\{8,\dots,T\}}\sum_{i\in I}x_{jkt}(\xi)$$

$$j \in J \qquad k \in K \qquad \xi \in SC$$

Subject to the constraint in the transportation at each day in the time horizon:

$$\sum_{\tau=\{1,\dots,t\}}\sum_{i\in I}\tilde{y}_{ijk\tau} \leq \sum_{\tau=\{1,\dots,t\}}\sum_{i\in I}\tilde{x}_{ijk\tau} \qquad j \in J \qquad k \in K \qquad \mathrm{t} \in \{1,\dots,7\}$$

$$\sum_{\tau=\{1,\dots,7\}}\sum_{i\in I}\tilde{y}_{ijk\tau} + \sum_{\tau=\{8,\dots,t\}}\sum_{i\in I}y_{ijk\tau}(\xi) \leq \sum_{\tau=\{1,\dots,7\}}\sum_{i\in I}\tilde{x}_{ijk\tau} + \sum_{\tau=\{8,\dots,t\}}\sum_{i\in I}x_{ijk\tau}(\xi)$$

$$j \in J \quad k \in K \quad \mathrm{t} \in \{8,\dots,T\} \quad \xi \in SC$$

Subject to the constraint in the non-negative properties of the variables:

$$\tilde{x}_{ijkt}, \tilde{y}_{ijkt}, \tilde{v}_{jkt} \in \{0,1,2,\dots\} \qquad i \in I \quad j \in J \quad k \in K \quad t \in \{1,\dots,7\}$$

$$x_{ijkt}(\xi), y_{ijkt}(\xi), v_{jkt}(\xi) \in \{0,1,2,\dots\} \qquad i \in I \quad j \in J \quad k \in K \quad t \in \{8,\dots,T\} \quad \xi \in SC$$

In this model, C_1 is the cost and L_1 is the delay for the first week in the planning period, which is supposed to be fixed. C_2 is the cost and L_2 is delay for the following three weeks in the planning period, which is subjected to uncertainty with the set of weighted realized scenarios ξ.

To solve this problem with two objectives, we consider a set of λ values that is within the range [0, 1] and solve a set of optimization models with the objective function as $f = \lambda(C_1 + C_2) + (1 - \lambda)(L_1 + L_2)$. The set of optimal values for $C_1 + C_2$ and $L_1 + L_2$ achieved from these optimization models forms the Pareto frontier. When $\lambda = 1$, the solution minimizes cost, and when $\lambda = 0$, the solution minimizes delay. For the intermediate values of λ, we get Pareto optimal solutions along the efficient frontier (Rardin, 1998; Winston, 2004).

6.4 EXAMPLE PROBLEM

Consider a four-week planning period (28 days) of a CP&M supply chain network that includes three fabrication shops and ten construction projects (ten jobs) situated at different locations.

These jobs require different types of job parts at different days in the 4-week planning horizon. The total number of unique job parts demanded by these jobs is fifteen. Each shop has different production times and production costs. These shops work seven days per week, two shifts per day and eight hours per shift. As a result, the number of machine hours per day available for production is $\tilde{h}$=16. There is a penalty cost for each day of delay past the required delivery time for each unit of job part. The shop managers develop schedules based on a four-week plan that includes one weekly work plan for the first week and a look-ahead plan for the next three weeks. Because it is common that the delivery times could be changed based on construction schedules, the shop managers need to consider uncertainty when developing their production plan. They need to determine the job allocation, production schedules and transportation schedules of these fabrication shops considering different scenarios about required delivery times. They also want to understand the tradeoff between minimizing cost and minimizing delay to create a flexible schedule that balances these objectives.

Four scenarios for the stochastic programming model are developed. Scenario 1 indicates the original due dates that have been agreed between the fabricator and construction projects. In Scenario 2, the original due dates are postponed for around 30%-40% of job parts for three days. In Scenario 3, the original due dates are shifted for three days earlier for around 30%-40% of job parts. In Scenario 4, the original due dates are postponed for around 30%-40% of job parts of job 1 to job 5 for three days. In Scenario 4, the original due dates for around 30%-40% of job parts of job 6 to job 10 are shifted for three days earlier. Since the schedule for week 1 is developed based on uncertainty of the required delivery time in the next three weeks in the planning period, the due dates in Scenarios 2, 3 and 4 are limited within day 8 to day 28.

Tables 6.2 to 6.5 describe the input data used in this example problem.

Table 6.2 Transportation distance between construction sites and fabrication shops

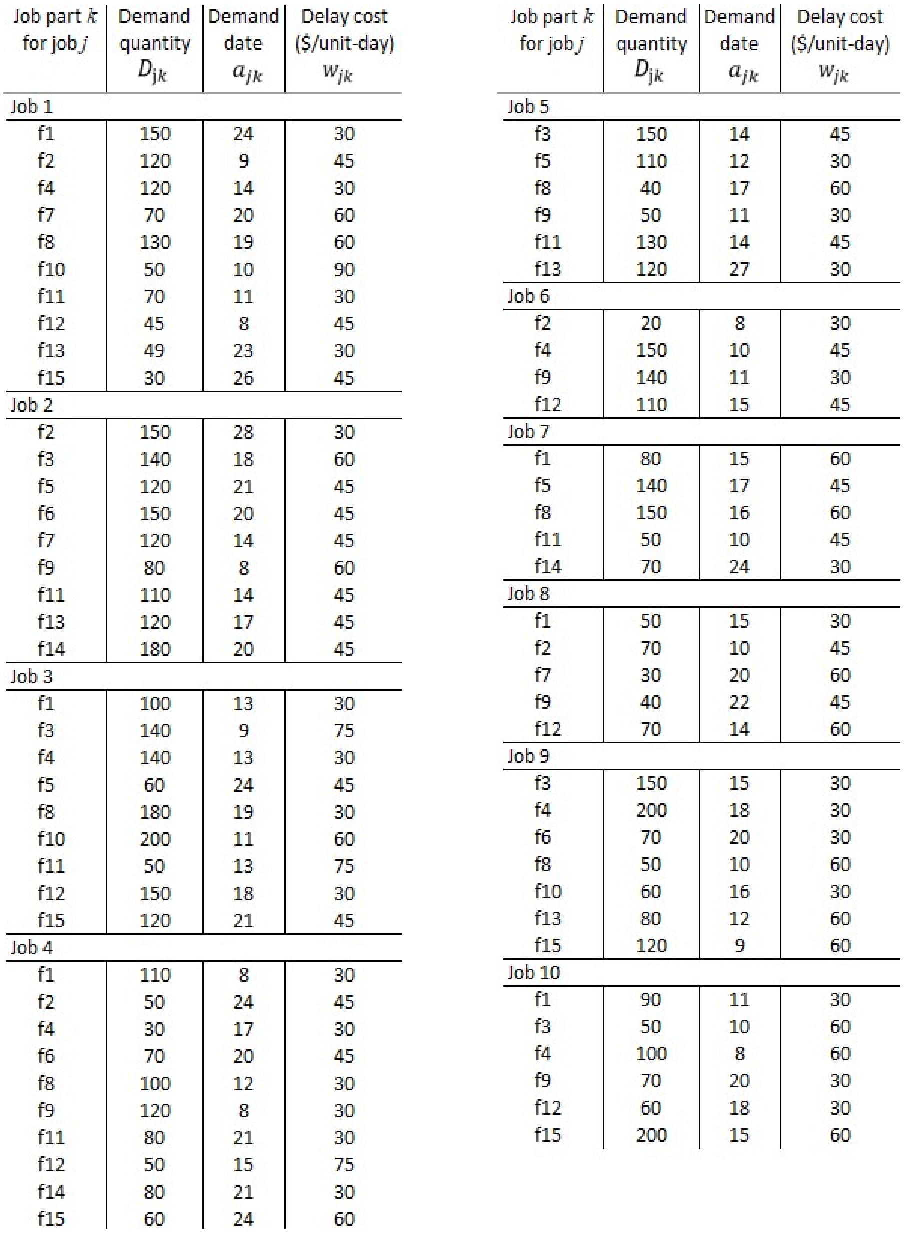
Transportation Distance (km) d_{ij}

Job j	Shop 1, i = 1	Shop 2, i = 2	Shop 3, i = 3
Job 1	50	65	10
Job 2	69	85	90
Job 3	76	79	25
Job 4	60	80	70
Job 5	79	42	150
Job 6	150	90	40
Job 7	80	70	60
Job 8	50	90	80
Job 9	130	20	40
Job 10	100	60	110

Table 6.3 Transportation cost, production cost and production time at different shops

Job part k	Transportation cost ($/unit/km) c_k^m	Production time (hour/unit) p_{ik}			Production cost ($/unit) c_{ik}^p		
		Shop 1 i = 1	Shop 2 i = 2	Shop 3 i = 3	Shop 1 i = 1	Shop 2 i = 2	Shop 3 i = 3
f1	0.9	2	2	1	450	405	405
f2	0.9	3	2	3	720	720	720
f3	0.6	4	3	2	960	1152	1152
f4	0.9	2	1	4	360	288	288
f5	1.2	3	2	2	540	432	432
f6	1.2	2	2	1	480	384	384
f7	1.5	1	1	2	180	144	144
f8	0.9	2	2	1	480	384	384
f9	1.2	2	3	3	600	900	900
f10	0.6	1	2	1	180	270	270
f11	1.2	3	4	2	720	1080	1080
f12	0.3	1	1	2	180	216	216
f13	0.3	2	1	2	480	288	288
f14	0.6	5	3	3	540	864	864
f15	0.9	2	2	3	360	396	396

Table 6.4 Demand quantity, original due date and delay cost of different construction projects



Job part k for job j	Demand quantity D_{jk}	Demand date a_{jk}	Delay cost ($/unit-day) w_{jk}
Job 1			
f1	150	24	30
f2	120	9	45
f4	120	14	30
f7	70	20	60
f8	130	19	60
f10	50	10	90
f11	70	11	30
f12	45	8	45
f13	49	23	30
f15	30	26	45
Job 2			
f2	150	28	30
f3	140	18	60
f5	120	21	45
f6	150	20	45
f7	120	14	45
f9	80	8	60
f11	110	14	45
f13	120	17	45
f14	180	20	45
Job 3			
f1	100	13	30
f3	140	9	75
f4	140	13	30
f5	60	24	45
f8	180	19	30
f10	200	11	60
f11	50	13	75
f12	150	18	30
f15	120	21	45
Job 4			
f1	110	8	30
f2	50	24	45
f4	30	17	30
f6	70	20	45
f8	100	12	30
f9	120	8	30
f11	80	21	30
f12	50	15	75
f14	80	21	30
f15	60	24	60
Job 5			
f3	150	14	45
f5	110	12	30
f8	40	17	60
f9	50	11	30
f11	130	14	45
f13	120	27	30
Job 6			
f2	20	8	30
f4	150	10	45
f9	140	11	30
f12	110	15	45
Job 7			
f1	80	15	60
f5	140	17	45
f8	150	16	60
f11	50	10	45
f14	70	24	30
Job 8			
f1	50	15	30
f2	70	10	45
f7	30	20	60
f9	40	22	45
f12	70	14	60
Job 9			
f3	150	15	30
f4	200	18	30
f6	70	20	30
f8	50	10	60
f10	60	16	30
f13	80	12	60
f15	120	9	60
Job 10			
f1	90	11	30
f3	50	10	60
f4	100	8	60
f9	70	20	30
f12	60	18	30
f15	200	15	60

Table 6.5 Scenarios about required delivery time

Job part k for job j	Demand Date at Scenario (SC) a_{jk}			
	SC1	SC2	SC3	SC4
Job 1	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Move back SC1 duedate*
f1	24	27	21	21
f2	9	12	8	8
f4	14	17	11	11
f7	20	20	20	20
f8	19	19	19	19
f10	10	10	10	10
f11	11	11	11	11
f12	8	8	8	8
f13	23	23	23	23
f15	26	26	26	26
Job 2	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Move back SC1 duedate*
f2	28	28	28	28
f3	18	18	18	18
f5	21	24	18	18
f6	20	23	17	17
f7	14	17	11	11
f9	8	8	8	8
f11	14	14	14	14
f13	17	17	17	17
f14	20	20	20	20
Job 3	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Move back SC1 duedate*
f1	13	13	13	13
f3	9	9	9	9
f4	13	13	13	13
f5	24	24	24	24
f8	19	22	19	16
f10	11	14	8	8
f11	13	16	10	10
f12	18	18	15	18
f15	21	21	21	21
Job 4	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Move back SC1 duedate*
f1	8	8	8	8
f2	24	24	24	24
f4	17	17	17	17
f6	20	20	20	20
f8	12	12	12	12
f9	8	8	8	8
f11	21	21	21	21
f12	15	18	15	12
f14	21	24	18	18
f15	24	27	21	21

Job part k for job j	Demand Date at Scenario (SC) a_{jk}			
	SC1	SC2	SC3	SC4
Job 5	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Move back SC1 duedate*
f3	14	17	11	11
f5	12	15	9	8
f8	17	20	14	14
f9	11	11	11	11
f11	14	14	14	14
f13	27	27	27	27
Job 6	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Extend SC1 duedate*
f2	8	11	8	8
f4	10	13	10	10
f9	11	11	8	14
f12	15	15	12	18
Job 7	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Extend SC1 duedate*
f1	15	15	12	18
f5	17	17	17	17
f8	16	19	16	16
f11	10	13	10	10
f14	24	24	21	27
Job 8	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Extend SC1 duedate*
f1	15	18	15	15
f2	10	10	8	13
f7	20	20	17	23
f9	22	22	22	22
f12	14	17	14	14
Job 9	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Extend SC1 duedate*
f3	15	18	15	15
f4	18	21	18	18
f6	20	20	20	20
f8	10	10	10	10
f10	16	16	13	19
f13	12	12	9	15
f15	9	9	9	9
Job 10	*Original*	*Extend SC1 duedate*	*Move back SC1 duedate*	*Extend SC1 duedate*
f1	11	11	8	14
f3	10	10	10	10
f4	8	8	8	8
f9	20	23	20	20
f12	18	21	18	18
f15	15	15	12	18

(*The numbers in red color indicate the required delivery time that are changed compared to the original required delivery time)*

6.5 COMPUTATIONAL RESULT

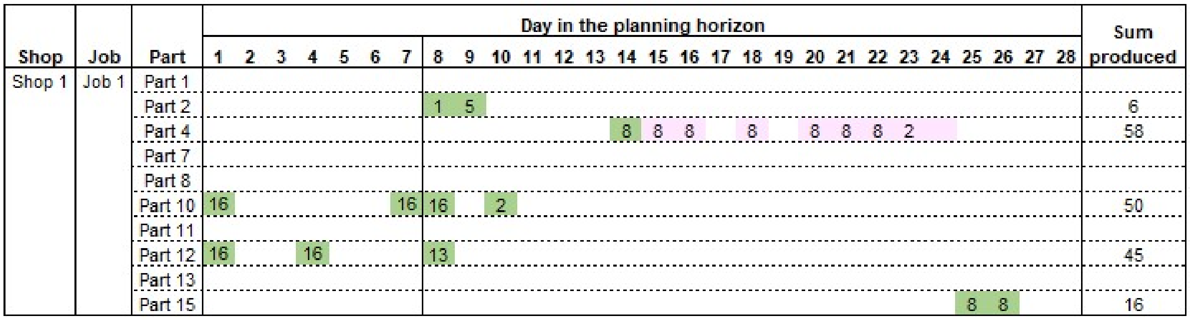
Computational Run-time

As discussed earlier, I use DOCPLEX (version 2.9.141, 2019) with an Intel® Core™ i7-5500U CPU@2.40GHz laptop to solve the example problem. The run-time for a problem with a single scenario and single objective is approximately 10 seconds; for the two-stage stochastic programming with four scenarios and single objective is approximately 25 seconds. However, when exploring the Pareto optimal solutions along the efficient frontier with 20 values of λ and the two-stage stochastic programming with four scenarios, the run-time is approximately 15 minutes because multiple models are needed to generate several points along the efficient frontier.

Production Schedule

To understand the performance of the stochastic (SC) model that has no uncertainty by including a single scenario compared to the stochastic model that has uncertainty by including four scenarios, I solved the SP model with a single scenario for the example problem using the due date in Scenario 1. Table 6.6 shows the production schedule in shop 1 for job 1 generated from this model. Table 6.7 shows the production schedule in shop 1 for job 1 generated from the SP model with four scenarios. The complete schedules are included in the Appendixes of this dissertation. Both SP models with a single scenario and with four scenarios focus on minimizing cost (by assigning the value of $\lambda = 1$). The computational results show that the total cost generated from the SP model with a single scenario using Scenario 1 and the total cost generated from the SP model with four scenarios when selecting the solution for Scenario 1 are the same and equal to $4,289,087. However, the production schedules at the first seven days for the solution for Scenario 1 are different from these models. This difference indicates the robustness of the stochastic programming (SP) model. As mentioned previously, the SP model developed in this study presents the problem that the required delivery time of the first week (or weekly work plan) is determined, however, the required delivery time of the coming weeks are subjected to changes. Therefore, the SP model with four scenarios fixes the production schedule in the first seven days for all scenarios but results in different production schedules for the remaining time in the planning horizon for different scenarios. The SP model with four scenarios changes the production schedule for the first seven days comparing to that of the SP model with a single scenario to allow the adaption of the production planning in the remaining time to achieve the same optimal value for the same scenario with the case that has no uncertainty (the case that has a single scenario).

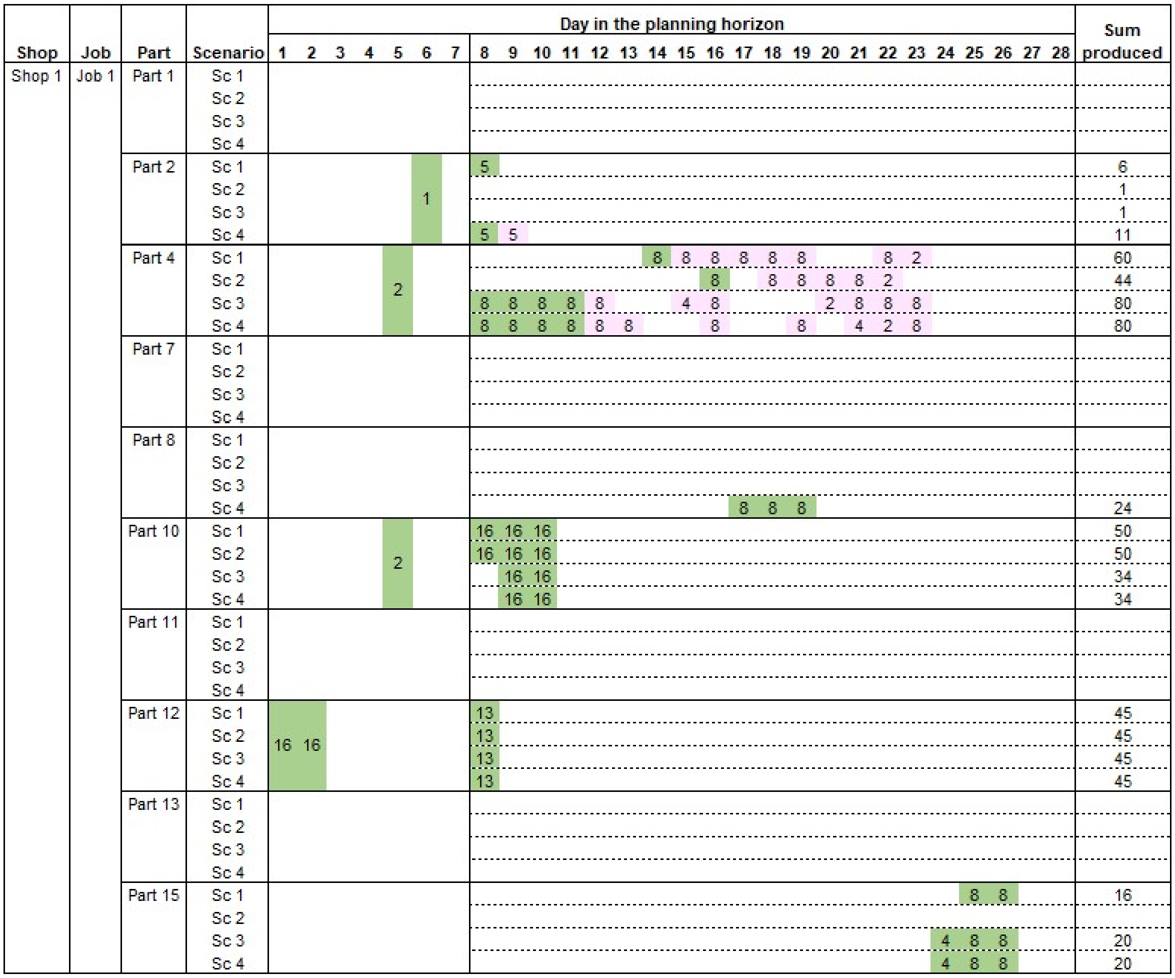
Table 6.6 Production schedule at shop 1 for job 1 per the SP model with single scenario at SC1



Shop	Job	Part	Day in the planning horizon																												Sum produced
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
Shop 1	Job 1	Part 1																													
		Part 2								1	5																				6
		Part 4														8	8	8		8		8	8	8	2						58
		Part 7																													
		Part 8																													
		Part 10	16						16	16		2																			50
		Part 11																													
		Part 12	16			16				13																					45
		Part 13																													
		Part 15																									8	8			16

(The number in each cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy)

Table 6.7 Production schedule of shop 1 for job 1 per the SP model with four scenarios



Shop	Job	Part	Scenario	Day in the planning horizon																												Sum produced
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
Shop 1	Job 1	Part 1	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 2	Sc 1						1		5																					6
			Sc 2																													1
			Sc 3																													1
			Sc 4								5	5																				11
		Part 4	Sc 1					2									8	8	8	8	8	8			8	2						60
			Sc 2																8		8	8	8	8	2							44
			Sc 3								8	8	8	8	8			4	8				2	8	8	8						80
			Sc 4								8	8	8	8	8	8			8			8		4	2	8						80
		Part 7	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 8	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																	8	8	8										24
		Part 10	Sc 1					2			16	16	16																			50
			Sc 2								16	16	16																			50
			Sc 3									16	16																			34
			Sc 4									16	16																			34
		Part 11	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 12	Sc 1	16	16						13																					45
			Sc 2								13																					45
			Sc 3								13																					45
			Sc 4								13																					45
		Part 13	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 15	Sc 1																									8	8			16
			Sc 2																													
			Sc 3																								4	8	8			20
			Sc 4																								4	8	8			20

(The number in each cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy)

Optimal Costs at Various Scenarios:

Figure 6.2 shows the optimal costs at different scenarios generated by the SP model that focuses on minimizing total cost (λ = 1). The first set of bars in Figure 6.2 is for the SP model that consider four scenarios by randomly assigning possibility of occurring for scenarios 1, 2, 3 and 4 as 40%, 30%, 10% and 20%, respectively. The next four sets of bars in Figure 6.2 is for the SP model that considers single scenarios, the second set is for Scenario 1, the third set is for Scenario 2, the fourth set is for Scenario 3, the fifth set is for Scenario 4. The optimal cost of the SP model with four scenarios is $4,279,240, within the range of the optimal costs generated for scenarios 1 to 4. Scenario 2 has the smallest optimal cost at $4,211,765, and scenario 3 has the largest optimal cost at $4,352,764. This is reasonable since scenario 2 represents the case that the due dates are extended later from scenario 1, giving the supply chain more flexibility to arrange schedule and find smaller cost. On the other hand, scenario 3 represents the case that the due dates are shifted earlier from scenario 1, making it difficult for the supply chain to arrange schedule and resulting in higher cost. The optimal cost of scenario 4 is $4,313,714, within the middle since this scenario presents the case that some due dates are shifting earlier, some due dates are shifting later, so the optimal cost should be somewhere between the best case and worst case. Note that the model does not include handling cost for the works impacted by the changes in required delivery time.

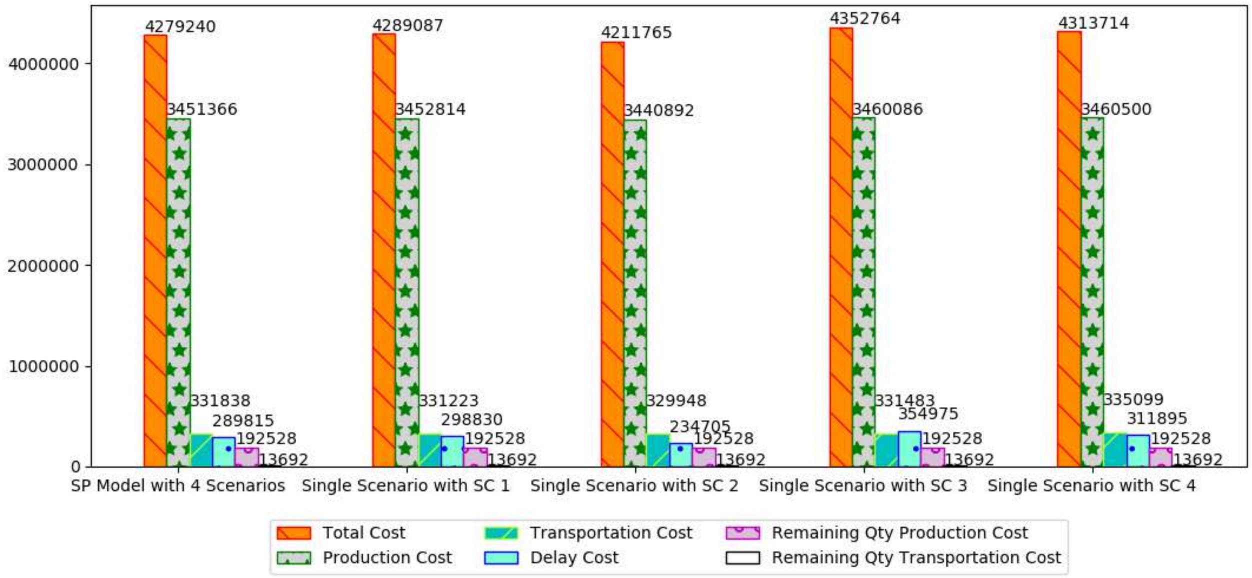


Figure 6.2 Optimal cost generated from the SP model with four scenarios and the SP model with single scenarios (no handling cost is included)

When a handling cost is included in the cost function, the total cost increases as indicated in Table 6.8 and Figure 6.3. Similar to the example problem presented in Chapter 5, the handling cost is estimated as 15% of the average cost to produce the job parts whose required delivery time is varied.

Table 6.8 Optimal cost for different cases with variable delivery times

	Without handling cost		With handling cost	
Case	Cost ($)	% change from the case with SC1	Cost ($)	% change from the case with SC1
SP model for single scenario with SC1	4,289,087		4,289,087	
SP model for single scenario with SC2	4,211,765	-1.80	4,287,259	-0.04
SP model for single scenario with SC3	4,352,764	1.48	4,414,771	2.93
SP model for single scenario with SC4	4,313,714	0.57	4,381,373	2.15
SP model with four scenarios	4,279,240	-0.23	4,321,620	0.76

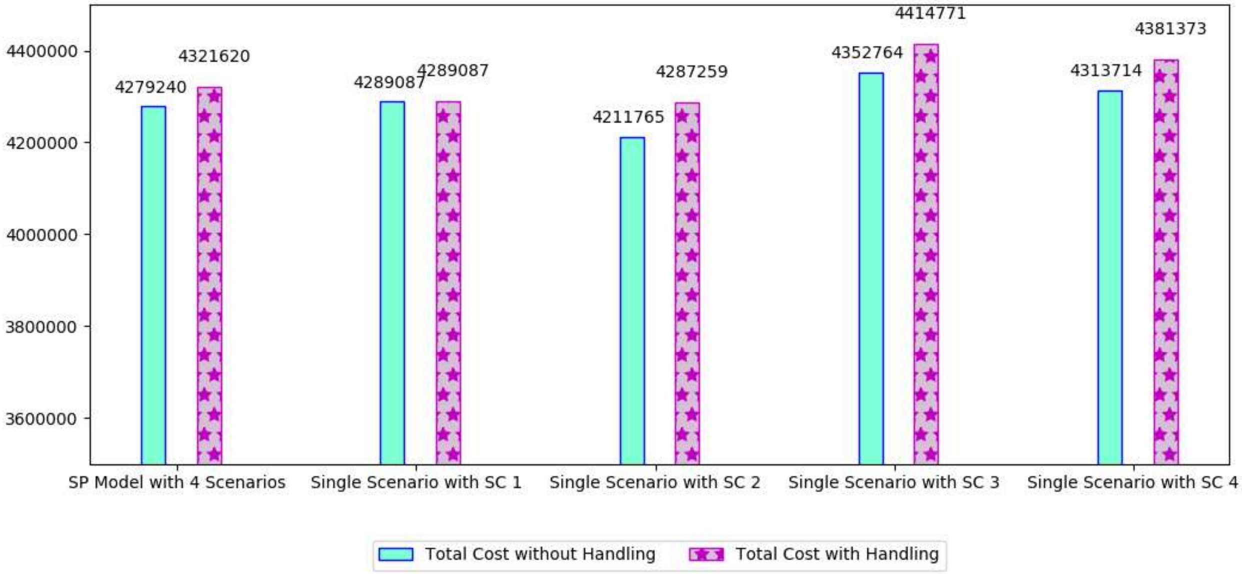


Figure 6.3 Optimal cost generated from the SP models with four scenarios and with single scenario for the cases without a handling cost and with handling cost

As shown in Table 6.8, the total cost that includes a handling cost generated from the SP model for a single scenario with Scenario 3 is increased 2.93% compared to that for Scenario 1 (the scenario that has no change in the required delivery time). This is the highest increase compared to other scenarios as Scenario 3 is the least favorable case when the due dates are shifted earlier compared to the original case.

It shows that the total cost with handling cost of the case with Scenario 2 is decreased lightly at 0.04%, comparing to 1.8% decrease of the case without total handling cost. Remember that Scenario 2 is the most favorable case where the due dates are postponed compared to the original case, giving the supply chain more flexibility to find a schedule with lower cost. This indicates that although postponing jobs could give the supply chain more opportunity to find smaller cost, the handling cost required to handle the changes could offset the reduction cost gaining from having higher flexibility.

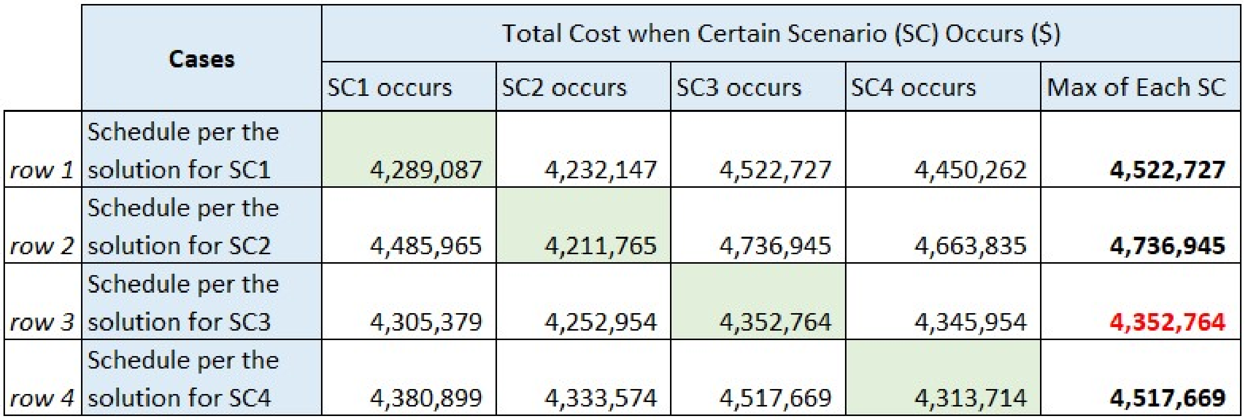
It also shows that the increase in the total cost considering to the handling cost generated from the example problem in this chapter is smaller than the increase generated from the example problem in Chapter 5. The increase also varies depending on different scenarios. This is reasonable since the example in Chapter 5 assumes that most of the works have changes in required delivery time, while the example in this Chapter assumes that the required delivery time varies for only 30-40% of the works. The different in unit costs between two examples problems also causes the different in the impact of the handling cost.

This example problem indicates that when including a handling cost to handle the variation in required delivery time, the total cost increases from -0.04% to 2.93%. This example problem considers the cases where the required delivery time could be shifted earlier or later, and the variation applied for 30-40% of the works. The changes in total cost obtained from this example is reasonable since the percent of works are changed in the required delivery time is determined from previous studies and the industry survey. The industry survey carried out in the course of this research reveals that most fabricators accept and bear the cost caused by the changes in the required delivery time initiated from the changes in schedule of construction projects. It also reveals that some fabricators have to add more cost to account for the changes from bidding process. While the small range of increase in total cost from -0.04% to 2.93% could explains the reason why most fabricators accept and bear the cost caused by the changes in delivery time by themselves, it is a fact that the inclusion of additional cost from bidding process contributes to the increase in the cost of construction projects and impact their end users.

Selection of a Solution with Minimal Risk

While the SP model could generate optimal production schedules for the supply chains subject to predicted scenarios about uncertainty, in real life, construction fabricators must select a solution for their production process. A question that was raised up is what happens if a fabricator carries out the production process based on a scenario, but another scenario occurs. Which scenario should be chosen to avoid getting an overly high cost under unfavorable scenarios? Table 6.9 shows the answer of this question. Table 6.9 is generated by solving the SP model with a single scenario for a certain scenario (say scenario A), then applying the due date of another scenario (say scenario B) to the optimal schedule generated for scenario A and calculate the total cost.

Table 6.9 Total cost when planning per the solution of a scenario but another scenario occurred

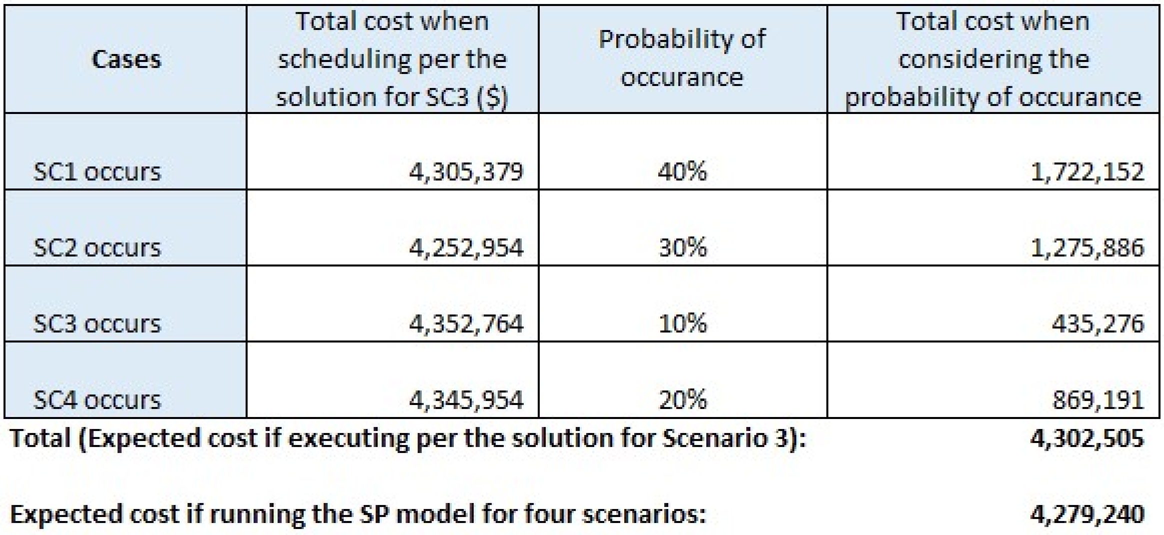


	Cases	Total Cost when Certain Scenario (SC) Occurs ($)				
		SC1 occurs	SC2 occurs	SC3 occurs	SC4 occurs	Max of Each SC
row 1	Schedule per the solution for SC1	4,289,087	4,232,147	4,522,727	4,450,262	**4,522,727**
row 2	Schedule per the solution for SC2	4,485,965	4,211,765	4,736,945	4,663,835	**4,736,945**
row 3	Schedule per the solution for SC3	4,305,379	4,252,954	4,352,764	4,345,954	**4,352,764**
row 4	Schedule per the solution for SC4	4,380,899	4,333,574	4,517,669	4,313,714	**4,517,669**

Row 1 in Table 6.9 shows the total costs when scheduling per scenario 1, but another scenario occurs. Similarly, row 2, row 3, row 4 show the total cost when scheduling per scenario 2, scenario 3, scenario 4, respectively, but another scenario occurs. The last column in Table 6.8 presents the maximal cost that is incurred when carrying out the production process per each scenario. The solution that provides the best balance between yielding a low cost under a good scenario and avoiding an overly high cost under adverse scenarios should be the solution that results in the minimal cost under the worst scenario. Comparing the result from Table 6.9, the supply chain manager should plan the production per the solution for scenario 3 that results in $4,352,764 when the worst scenario happens.

Table 6.10 presents the total cost considering probability of occurrence when planning per the solution for scenario 3 but another scenario occurs. With the probability of occurrent of these scenarios that are randomly selected as 40%, 30%, 10%, 20% for scenarios 1, 2, 3, 4, the total cost is $4,302,505. This value is higher than the total cost at $4,297,240 generated by the SP model with four scenarios considering the same probability of occurrence (see Figure 6.2). The result indicates that the SP model that considers all scenarios generates a better solution than the model that considers single scenarios and then applies the probability of occurrence. As a result, this confirms the robustness of stochastic programming model.

Table 6.10 Total cost considering probability of occurrence when planning per the solution for Scenario 3 but another scenario occurred



Cases	Total cost when scheduling per the solution for SC3 ($)	Probability of occurance	Total cost when considering the probability of occurance
SC1 occurs	4,305,379	40%	1,722,152
SC2 occurs	4,252,954	30%	1,275,886
SC3 occurs	4,352,764	10%	435,276
SC4 occurs	4,345,954	20%	869,191

Total (Expected cost if executing per the solution for Scenario 3): 4,302,505

Expected cost if running the SP model for four scenarios: 4,279,240

Multi-objective Optimization

Figure 6.3 shows the Pareto frontier for scenario 1 with the tradeoffs between cost and delay. The figure indicates that the smaller the cost, the higher the delay and vice versa, the smaller the delay, the higher cost. If the supply chain managers choose the smallest cost, they may suffer a significant delay. On the other hand, if they choose the smallest delay, they may suffer a very high cost. When delay reduces from 8,501 to 8,116 (4.54% reduction), the cost increases mildly from $4,279,259 to $4,282,179 (0.07% increase). There is a region where the cost increases significantly from $4,282,179 to $4,459,249 (3.83% increase) when delay is reduced from 8,116 to 7,790 (4% reduction). A supply chain manager may choose to balance between cost and delay and select a point in the Pareto frontier with an acceptable delay and a reasonable cost. The Pareto frontier also shows some points with the same cost at $4,279,240 but different delays. This is the same optimal cost obtained from the optimization problem with a single objective focusing on minimizing cost. This indicates that the optimization problem with a single objective focusing on minimizing cost has multi optima (or multi optimal solutions).

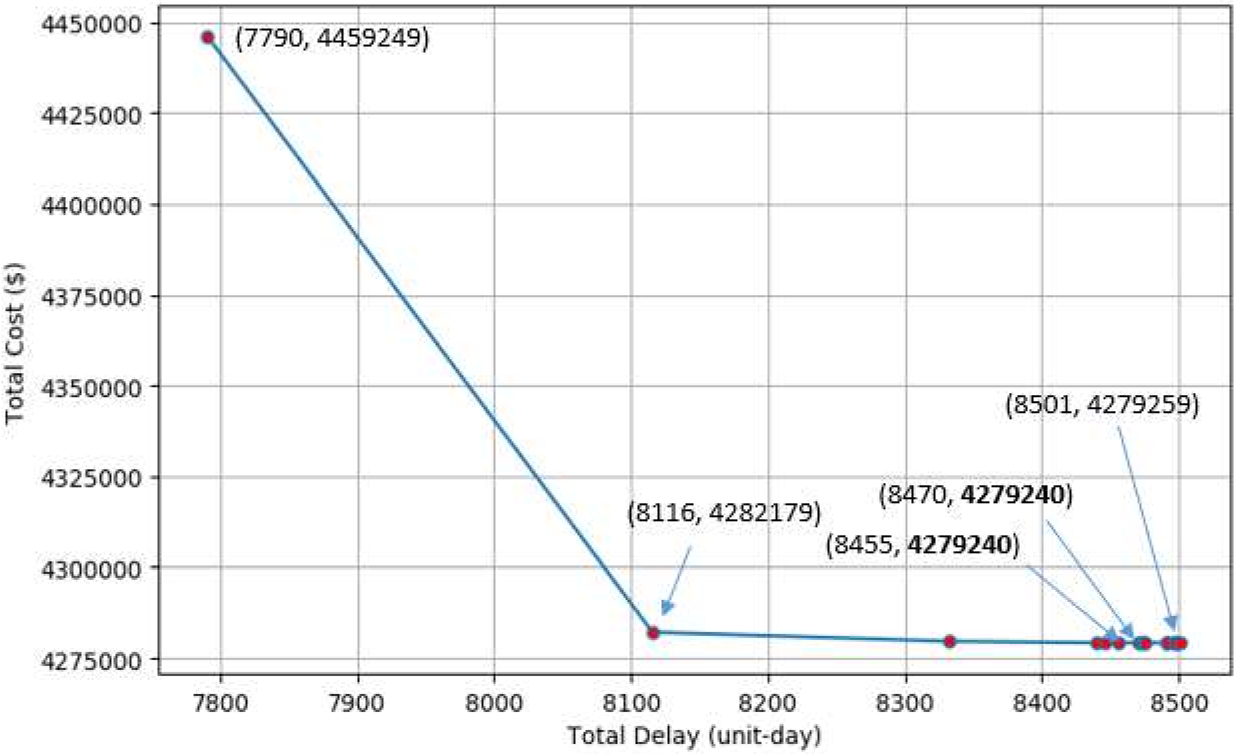
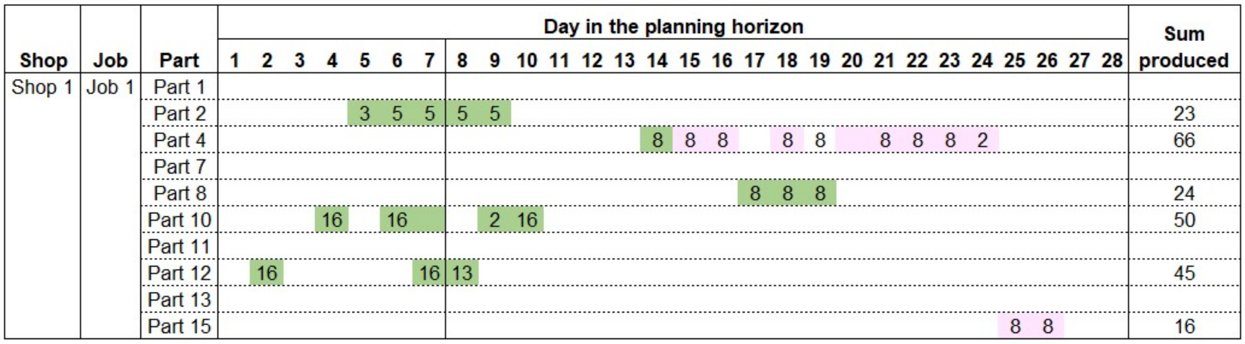


Figure 6.4 Pareto frontier achieved from the SP model with four scenarios

Tables 6.11 and 6.12 show the production schedules at shop 1 for job 1 corresponding to the optimal solution that balances cost and delay with the total cost at $4,282,179 and the total delay at 8,116. Table 6.11 is the production schedule generated by the stochastic programing (SP) model with a single scenario at the Scenario 1, and Table 6.11 is the production schedule generated by the SP model with four scenarios. Similar to Table 6.6 and Table 6.7, it shows that the schedule at week 1 for Scenario 1 generated by the SP model with four scenarios is different from the schedule at week 1 for Scenario 1 generated by the SP model with a single scenario. This is because the SP model with four scenarios changes the production schedule to adapt different scenarios while still obtaining the best possible solution. However, in Tables 6.11 and 6.12, more works are performed in week 1 compared to the production schedules per Tables 6.6 and 6.7 since the models corresponding to Tables 6.11 and 6.12 try to reduce the delay together with reducing cost to balance cost and time objectives.

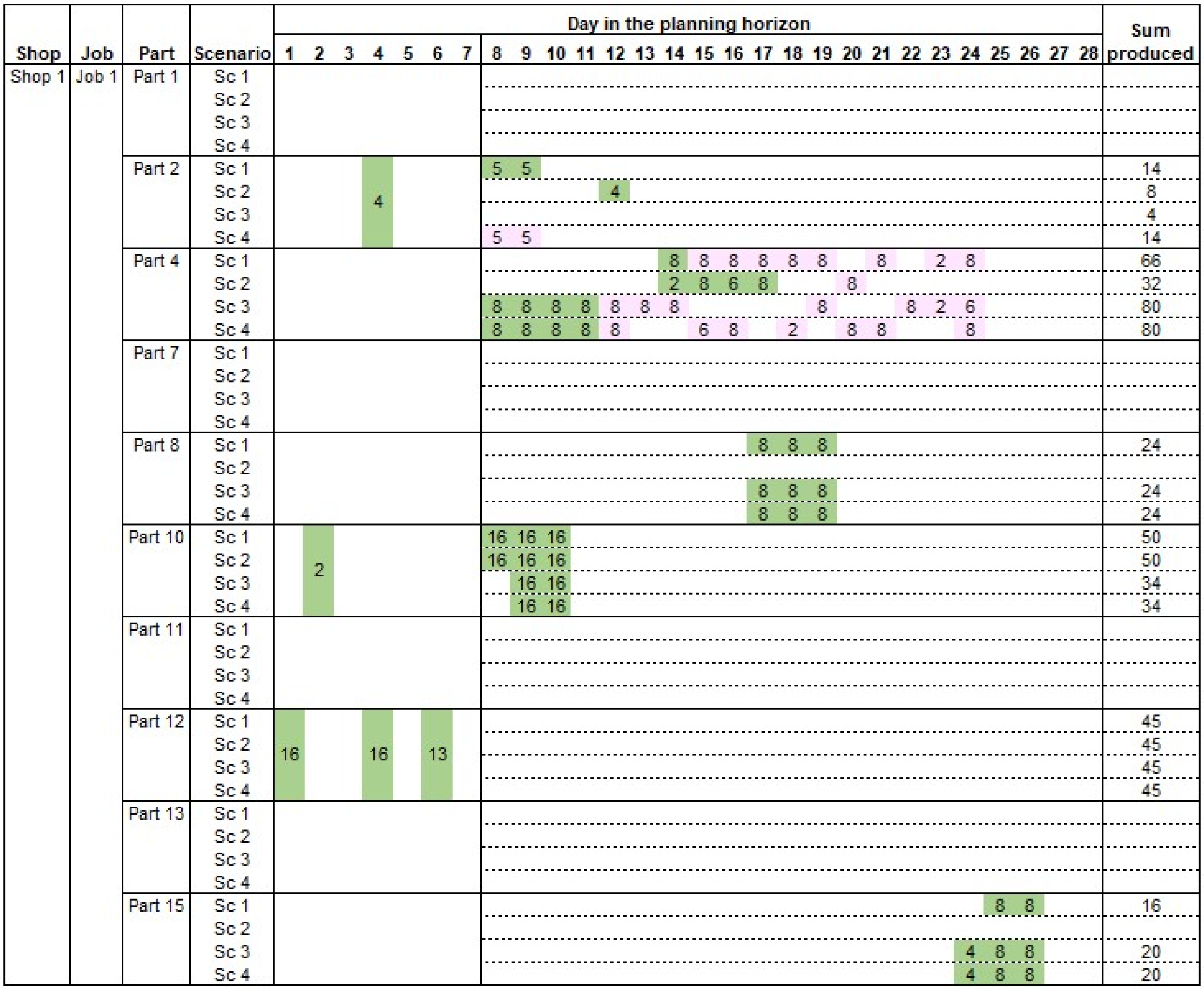
Table 6.11 Production schedule at shop 1 for job 1 per the multi-objective SP model with single scenario at SC1



Shop	Job	Part	Day in the planning horizon																												Sum produced
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
Shop 1	Job 1	Part 1																													
		Part 2					3	5	5	5	5																				23
		Part 4														8	8	8		8	8		8	8	8	2					66
		Part 7																													
		Part 8																	8	8	8										24
		Part 10				16		16			2	16																			50
		Part 11																													
		Part 12		16					16	13																					45
		Part 13																													
		Part 15																									8	8			16

(The number in each cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy)

Table 6.12 Production schedule of shop 1 for job 1 per the multi-objective SP model with four scenarios



				Day in the planning horizon																											
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum produced
Shop 1	Job 1	Part 1	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 2	Sc 1				4				5	5																				14
			Sc 2												4																	8
			Sc 3																													4
			Sc 4								5	5																				14
		Part 4	Sc 1														8	8	8	8	8	8		8		2	8					66
			Sc 2														2	8	6	8			8									32
			Sc 3								8	8	8	8	8	8	8					8			8	2	6					80
			Sc 4								8	8	8	8	8			6	8		2		8	8			8					80
		Part 7	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 8	Sc 1																	8	8	8										24
			Sc 2																													
			Sc 3																	8	8	8										24
			Sc 4																	8	8	8										24
		Part 10	Sc 1		2						16	16	16																			50
			Sc 2								16	16	16																			50
			Sc 3									16	16																			34
			Sc 4									16	16																			34
		Part 11	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 12	Sc 1	16			16		13																							45
			Sc 2																													45
			Sc 3																													45
			Sc 4																													45
		Part 13	Sc 1																													
			Sc 2																													
			Sc 3																													
			Sc 4																													
		Part 15	Sc 1																									8	8			16
			Sc 2																													
			Sc 3																								4	8	8			20
			Sc 4																								4	8	8			20

(The number in each cell is the quantity produced on that day, the number in the purple cell is the quantity produced on that day but tardy)

Current construction contract terms are normally locked in a fixed schedule. Once signing a contract, the fabricators must be responsible to meet the schedule. However, in case the schedule has a small variation, it is common that the fabricators manage the variation by themselves to solve their production planning to adapt with the changes and bear increasing cost due to the changes. Nevertheless, some fabricators have to estimate the potential changing cost and add that into their price from the bidding process, resulting in a higher cost for construction projects. The optimization model developed by this research opens an opportunity to inform main contractors about potential impact caused by the changes of the construction schedule. If the main contractors and fabricators have a system to share cost and schedule to run the developed SP model to generate production planning and optimal cost, then both parties could acknowledge early the impact of a schedule variation. This helps clarify the financial responsibility of each party when the schedule changes. As the main contractors are more informed about the cost impact of their decision in the construction schedule of prefabrication supply chains, they will take more caution when making changes to avoid incurring further cost, which benefits the contractors and the prefabrication supply chains.

6.6 SUMMARY

This chapter presents research about the application of optimization to facilitate the production planning of CP&M supply chains with multiple fabrication shops under uncertainty. To assist the production planning of this supply chain under the changes, this research presents the development of a stochastic programming model with a multi-objective optimization. The stochastic programming helps generate optimal production schedules at various scenarios provided that the required delivery time is unchanged in the first week (weekly work plan) but subject to changes in the remaining time of the planning horizon. The incorporation of a multi-objective optimization allows to create a set of schedules that balance the cost and time reduction objectives. The chapter also discusses computational results of an example problem with three fabrication shops, teen construction projects and fifteen job parts. The computational result shows that the stochastic model with four scenarios changes the production schedule of the first week (compared to the stochastic model with a single scenario) in order to adapt to various scenarios about uncertainty after the first week but still be able to generate the same optimal value with the deterministic model for the same realization of demands. It also indicates that there is a region in the Pareto frontier in which decreasing the delay could gradually increase the total cost. However, after the delay reduces to a certain value, a small reduction in the delay could cause a significant increase in the cost. Acknowledging the tradeoffs between cost and time via the Pareto frontier gives supply chain managers the flexibility to balance cost and time when designing their production planning. Moreover, this research suggests a method to help supply chain managers select a solution that avoids overly high cost when planning per one scenario, but an adversary scenario occurs.

Chapter 7. CONCLUSION

7.1 CONCLUSION

This dissertation presents research about construction prefabrication and modularization (CP&M) supply chains with an extensive literature review to understand improvement strategies for these supply chains. This work proposes an optimization model to assist the job allocations of the CP&M supply chains with multiple fabrication shops under variable delivery times. My study employs an interdisciplinary approach using methods from construction management and industrial engineering. This dissertation includes a literature reviews covering 110 CP&M papers. It discusses the results of two industry surveys to understand the operation of CP&M supply chains. It also presents the optimization models that facilitate job allocations and production planning of CP&M supply chains with multiple fabrication shops. Two example problems are created to demonstrate the optimization models, and computational results are discussed. Throughout the implementation of this study, the research questions addressed in Chapter 2 of this dissertation are resolved. These questions are as follows:

- Question 1: What are the improvement strategies for CP&M supply chains as suggested in the literature?
- Question 2: How does optimization support the production planning and job allocations of CP&M supply chains with multiple fabrication shops?
- Question 3: How does uncertainty in construction schedules impact the performance of CP&M supply chains and how to consider uncertainty when developing the production plan of CP&M supply chains with multiple fabrication shops?

The literature review suggests that there is a growing trend in the research about CP&M as the number of related studies has significantly increased in recent years. It shows the answer for research question 1 that various improvement strategies have been used for CP&M such as utilizing optimization, using simulation, focusing on product design, applying lean principles, using BIM and exploiting advanced technologies. It also suggests different best practices related to execution plans, management perspectives, vender issues, coordination and training to enhance the CP&M performance. Although utilizing optimization into production planning has been suggested in the literature, the number of studies in this area is still limited compared to the studies that focus on product design or building information modeling. The industry surveys also indicate that many prefabrication companies are operating multiple fabrication shops and allocate jobs between their shops, but there are few quantitative models available to quantify the outcome of allocation decisions. The conducted surveys also reveal that it is common for construction projects to change the required delivery time of prefabricated products, leading to additional costs for the fabricators to handle the changes. However, few researchers have addressed CP&M supply chains with multiple fabrication shops and considered uncertainty into the production planning of this supply chain.

To answer research question 2 and research question 3, two optimization models have been developed in this study. The first model is a deterministic model that does not incorporate into the model itself. The second model is a multi-objective stochastic programming model that incorporates uncertainty via various scenarios about required delivery time and considers cost and time reduction objectives. The stochastic programming helps generate optimal production schedules at various scenarios provided that the required delivery time is unchanged in the first week (weekly work plan) but subject to changes in the remaining time of the planning horizon. The incorporation of multi-objective optimization allows to create a set of schedules that balance the cost and time reduction objectives.

The example problem demonstrating the first optimization model is a CP&M supply chain with two fabrication shops, three construction projects and eight job parts. The computational results of this example problem show that the model could assist supply chain managers by finding the best possible solutions in allocating jobs and creating production schedules. The model generates an optimal solution with 2.5% cost reduction, compared to the solution generated by the traditional Early Due Date (EDD) method. Through a sensitivity analysis, the model helps identify the parameters sensitive to the changes, such as the availability of machine hours at certain time intervals and quantifies the impacts of these parameters on the supply chain performance. Moreover, the example problem examines the impact of variable delivery time by postponing the due date of construction project 1 at the end of week 1, construction project 2 at the end of week 2, construction project 3 at the end of week 3. It shows that postponing due dates in the middle of a production process could reduce the total cost by 0.49% because of the improved flexibility. However, postponing the due date could incur a handling cost that makes the total cost jump by 4.39%, well surpassing the savings achieved by the increased flexibility. Therefore, contractors are recommended to consider the impact of their demand variations on prefabrication supply chain performance. In addition, construction prefabricators should keep track of operational data, such as productivity rates and associated costs for management purposes and for implementing optimization and other advanced technologies.

The example problem demonstrates the second optimization model is an enlarged problem with three fabrication shops, ten construction jobs, fifteen job parts and four scenarios about variable delivery times. The computational results show that the stochastic model with all scenarios changes the production schedule at the first week compared with the stochastic model with single scenario. This makes the stochastic programming model adapt to various scenarios about uncertainty after the first week but still able to generate the same optimal value with the stochastic programming model with a single scenario for the same realization about required delivery times. Similar to the above example problem, this example problem examines the impact of changes in required delivery time to cost performance at different scenarios but by varying the due dates of 30%-40% of the works, some shifted earlier, some shifted later instead of postponing all due dates as in above example. This example problem shows that when considering the handling cost to handle the changes, the total cost could increase up to 2.93%. The computational results also indicate that there is a region in the Pareto frontier in which deceasing the delay could gradually increase the cost, but after the delay reduces to a certain value, a small reduction in delay could cause a considerable cost increase. Acknowledging the tradeoffs between cost and time via the Pareto frontier helps supply chain managers develop flexible production plans that could balance cost and time objectives. Moreover, this research proposes a method that allows to select a solution that avoids overly high cost when planning for one scenario but an unfavorable scenario occurs.

The construction industry lags behind the manufacturing industry due to its significant amount of waste and non-value-added activities (CII 2005). By shifting work to fabrication shops, the construction industry can utilize advanced technologies and supply chain management methods commonly used in the manufacturing sector. Considering the fact that most current construction contracts are locked in a fixed schedule, it is difficult for all parties to work together to reduce cost when the schedule changes. The stochastic programming model presented in this research opens an opportunity for construction stakeholders to quantify the impact of changes in required delivery time and work together to mitigate that. This research contributes to the improvement in production processes, thereby reducing costs and delays for prefabrication supply chains. This study is expected to help promote the application of prefabrication in construction, leading to a productivity improvement in the construction industry.

Although this research has performed surveys to understand industry practices and demonstrated the application of optimization into the production planning of CP&M supply chains, it has certain limitations. The surveys did not get to the point to achieve a detailed understanding of work breakdown structures, working sequences and shop schedules of different CP&M systems. This knowledge is critical and should be obtained in the future studies as it paves the brick for the further development of optimization models that are realistic and practical for CP&M supply chains. In addition, the models created in this research are based on some simplified assumptions, so the real production plans of CP&M supply chains are not entirely captured in the model. Finally, because of the limitation in time and resources, this research does not validate the application of the optimization models into practice via case studies.

7.2 POTENTIAL UTILIZATION OF OPTIMIZATION INTO THE PRODUCTION PLANNING OF CP&M

Although optimization has been used widely in many economic sectors, the surveys indicate that it is still uncommon in construction prefabrication and modularization. When CP&M companies operate on a small scale, with a small number of contracts and have extra capacity, they may find it not necessary to utilize optimization. However, with the growing interest in prefabrication and modularization, many fabrication companies operate on a larger scale with multiple fabrication shops, and many fabrication companies have a higher workload that requires them to work overtime and work more than one shift per day. The operation in a more complex manner and on a larger scale poses the need of applying optimization to enhance efficiency and performance. This research proposes an optimization model for the production planning of CP&M supply chains. However, the utilization of optimization into the production planning of CP&M supply chains as proposed in this research is still influenced by many factors. These factors can be classified into technical issues, management issues, operational issues, contractual issues and cultural issues. On one hand, the basic conditions to utilize optimization into practice are available. On the other hand, construction prefabrication and modularization still need further preparation to be able to successfully adopt it.

Technical Issues

Technical issues cover the availability of mathematic models, solver engines, data management platform, and skilled people that are needed for the development, computation and presentation of the results of optimization models. Operations research domains have developed many optimization algorithms and mathematic models to support the production planning covering various areas such as job shop schedules, worker timetable, working sequences, transportation routes and job allocations. Many solver engines are available to help solving optimization models such as CPLEX, AMPL (A Mathematic Programming Language), AIMMS (Advanced Interactive Multidimensional Modeling System), Gurobi Optimizer, etc. Some data management platforms have been created to support the smooth application of optimization in business such as the IBM Watson Studio that incorporates data collection, machine learning, optimization solver and presentation dashboard. However, the number of skilled people who are able to create optimization models, to use optimization solver engineers, and to present computational results is still small, especially in the field of construction. The practical adoption of optimization into CP&M requires that more people be educated and trained to understand and utilize optimization.

Management Issues

Similar to lean production, leadership is a key to success for the adoption of optimization into CP&M supply chains. At the starting point, it needs the willingness and support to utilize optimizations from the leaders. It also requires the necessary management of the leaders in order to effectively apply optimization into their production via deciding operations strategies and assigning responsibility over the supply chain. My surveys show that most leaders of prefabrication companies are interested in optimization. However, they are not ready to adopt it because of operational and human resource issues. Practical examples are also needed to convince them about the benefits of optimization. In addition, contractors and CP&M and should measure the reliability of construction schedules and use it as the input regarding the changes in required delivery times for the proposed optimization model. The more available data about the uncertainty of required delivery times, the more powerful the optimization model is. Moreover, this measurement will improve the awareness of the contractors about how reliable their schedules are and contribute to an effort to reduce the uncertainty.

Operational Issues

In order to develop the optimization models that are practical and suitable for the production planning of CP&M supply chains, the developers need a clear information about shop operations, workflow, work break down structure, productivity, demands, unit costs and other essential rules relating time buffer, transportation, inventory, delay penalty, etc. In addition, it is also necessary to consider the unique characteristic of the CP&M systems such as MEP, rebar, façade, precast, etc. in order to decide on a suitable scope of optimization. This requires CP&M companies to create a system to collect, organize and keep track of the data. The data is not only important for the adoption of optimization but also for management purposes and for the application of other advanced technologies in the future. My surveys reveal that most fabricators do not organize necessary data to prepare for the future utilization of optimization. Few companies keep track of productivity, however, this information is kept confidential, and therefore, the suitability of the achieved data on productivity is questionable.

Contractual Issues

The optimization model utilization as proposed in this research does not only provide support to the operations of CP&M supply chains, but could also be used to inform main contractors about the impact of uncertainty in the required delivery time on the performance of CP&M supply chains, from that to find a mitigation solution. To this day, a contract form named "Integrated Form of Agreement" has been used in lean construction to allow the shared benefits achieved from cost saving between owner, architect and contractor to encourage the architect and contractor to find better design solutions. However, there is no available contract form to facilitate the cost saving between main contractors and suppliers. The information sharing between the CP&M suppliers and main contractors regarding impact of uncertainty needs a similar contract form to encourage both parties looking for a mitigation decision. Also, there is a need to develop a data sharing system between both parties to provide information in a timely manner about the impact on cost and time performance.

Cultural Issues

The adoption of a new method is always challenging, and optimization is not an exception. As optimization is uncommon in this construction prefabrication and modularization, it could be met with resistance and considerable amount of doubt by the people implementing it. The imperative to achieve improved performance by applying the new method could also cause pressure on staffs and workers. To avoid such frustration, staffs need to be educated and trained the roles and expectations before utilizing optimization into the operations process.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

This research has delved deeply into reviewing the literature in CP&M supply chains, and more specifically, into applying optimization to support the production planning of these supply chains. In addition to answering the solving above research questions, this study also recognizes and suggests opportunities for future research, focusing on two main areas as described below.

Improvement Strategies for Construction Prefabrication and Modularization

The literature review carried out in this research indicates that although many improvement strategies were suggested for CP&M supply chains, most studies focused on product design and the application of Building Information Modeling, only a moderate number of studies paid attention to applying optimization in design, applying optimization in production planning and using simulations. The review of the areas of application and project types addressed in the literature about CP&M shows that a significant number of studies focused on the residential sector, but only few papers focused on the healthcare sector. While many studies are developed specifically for precast concrete and MEP systems, few studies consider prefabricated rebar and composite materials.

As a result, further research could focus on the areas that have not received adequate attention such as investigating further opportunities to apply optimizations into the design and production of CP&M systems, addressing the strategies to utilize CP&M in the healthcare sector, studying the application of prefabrication and modularization to rebar or composite materials.

In addition, one previous study has recognized that the feasibility of modularization in piping depends on piping systems, connection modes and project types (Li et al 2017b). Another study has established the factors influencing the benefit of prefabrication such as building type, location, logistics, prefabrication type, scale, repetition, standardization, level of innovation of contractor, environmental impact, project leadership, procurement type, site condition, site layout, client preference (Shazard 2016). Further research could refer to these factors of influence to develop further improvement strategies for construction prefabrication and modularization.

Applying Optimization to Support the Production Planning

The optimization models created in this study are based on some simplified assumptions. Future studies could improve these models by incorporating more factors such as inventory, labor, work sequences, rules regarding transportation. A number of studies in other industry sectors have addressed the optimization problems incorporating inventory, labor, work sequences, and transportation routes (Artigues et al. 2009, Bailey et al. 1995, Bard and Nananukul 2009). Certain optimization solvers such as CPLEX also include the techniques to solve complex planning and scheduling problems with mathematical programming and constraint programming. However, in order to effectively utilize optimization into the production planning of construction prefabrication and optimization, future studies should focus on getting a detail understanding about work breakdown structures, working sequences, and shop schedules of different CP&M systems and consider these unique characteristics when developing optimization models. Future research should also use real-time case studies to test the performance of the models to validate its performance and identify improvement opportunities.

On the other hand, while introducing optimization models to the main contractors could generate a common view about the impact of the uncertainty in construction schedules to the performance of CP&M supply chains, it cannot happen without a shared cost and schedule system between main contractors and suppliers. Further research should address this issue by trying to develop an effective method to timely inform main contractors about the quantitative impact of uncertainty of construction schedules on prefabrication supply chains in order to find mitigation solutions.

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APPENDIXES

VITA

Chung Thi Thu Ho was born in 1982 in Vinh city, Vietnam to Quang Ho and Hue Nguyen. She received a bachelor's degree in Construction Management in 2005 and a bachelor's degree in Structural Engineering in 2006 from the National University of Civil Engineering in Vietnam. She earned a master's degree in Structural Engineering from the University of Texas at Austin in 2010 with the sponsorship of the Vietnam Education Foundation (VEF). Chung started her PhD studies in Construction Management at the University of Washington in 2015 with a scholarship from the College of Built Environments. While pursuing her PhD, Chung worked as a teaching and research assistant at the University of Washington and interned at the Virtual Design Construction Department of Turner Construction Company in Seattle.

Appendix 1. INTERVIEW QUESTIONAIRE

Contract

1. Typically, how many construction projects does your company work for at the same time?
2. How many construction projects is your company working for currently?

Personnel

3. How many people in your company are:
   - Shop workers
   - Field workers
   - Office and technical staffs

Shop conditions

4. What is the working schedule of your fabrication shop: How many hours per shift, how many shifts per day, and how many days per week?
5. How long does it take from signing the contract to starting the fabrication?
6. What are the average times to fabricate and assemble typical jobs in your company?
7. How long do you keep the finished products in your shop before delivering to construction sites?
8. Who develop the shop schedule? What does he do to meet project's schedule and effectively utilizing shop resources (such as available workers, machines)?
9. How do you develop the production schedule for your fabrication shops? Do you use any software for the schedule (such as MS Project or Excel)?
10. What are the machines available in your fabrication shops? What is the productivity of these machines per hour? How many labors are needed to work for each machine?
11. Could you provide a copy of your fabrication schedule? (it could be with make-up data if you want to keep some information confidential)
12. Do you have data about production rates (machine, labor) to fabricate and assemble certain type of rebar? If yes, could you provide the information about the production rates? (it could be with make-up data if you want to keep some information confidential)
13. How many fabrication shops does your company have?
14. Do you allocate jobs and inventory between different fabrication shops?
15. If you allocate jobs and inventory between fabrication shops, then how do you make your allocation decisions?
16. Do you think a calculation tool to find the optimal cost for the job allocations between fabrication shops would be helpful for your company?
17. In case the job demand is higher than the current capacity of the current shop. What do you do?

Demand communication

18. How do you communicate with general contractors about the demand for fabrication materials?
19. How often do you communicate about the demand?
20. How reliable the demand is?
21. How does the uncertainty in demand impact the planning and scheduling of your fabrication shop?
22. What do you do to reduce the impact of demand uncertainty?

Construction Phase

23. How do you participate into the planning process of the construction projects, what are the benefit?
24. When does your company start ordering raw materials for a certain project?

25. When does your company start fabricating construction components for a certain project? Is that typically before or after signing the contract? If before signing the contract, what happen if the contract won't be signed, or if having design changes.
26. How to calculate the cost for the changes in delivery time, delay schedule, design changes, etc?
27. How does your company deal with the changes in the design and in the requirement about delivered time and quantity?
28. In case that your company delivers materials to a construction site, but the site is not ready to install, what will you do, leave the materials onsite or transport them back to the fabrication shop?

Optimization in Construction Prefabrication

29. Have you ever heard about optimizations and how optimizations are applied into the manufacturing sector?
30. Have your company ever applied optimizations into its fabrication production process?
31. Do you think optimizations would benefit the operations of your fabrication shop? If yes, how would optimizations benefit the operations of your fabrication shop?

Further Discussion

32. Types of prefabricated elements for given jobs: each job have certain types of elements, how to standardize these elements into group of types and get the data about production time for each type and use that for the scheduling/planning and optimizing the production process?
33. Difference between manufacturing and construction: Manufacturing is more consistent and has more data about productivities. Construction is unique and job-based but could the subcontractors be able to categorize their works into groups of elements and have certain data for each group of works/elements?
34. How to streamline the demand of construction projects with the workflow in manufacturing to maximize the utilization in manufacturing and take the advantage of optimization?
35. How lean construction could facilitate the application of optimization in construction prefabrication?

Thank you so much for your participation in this interview!!

INTERVIEWER
Chung Ho
PhD Candidate
Construction Management Department
University of Washington

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**					
Shop 1	Job 1	Part 1																															150	150	24
		Part 2						5			1																				6	6	120	120	9
		Part 3																																	
		Part 4														8	8	8				8	8	8	8	2					58	58	120	120	14
		Part 5																																	
		Part 6																																	
		Part 7																															70	70	20
		Part 8																															130	130	19
		Part 9																																	
		Part 10	16						16	16		2																			50	50	50	50	10
		Part 11																															70	70	11
		Part 12			16				13	16																					45	45	45	45	8
		Part 13																															49	49	23
		Part 14																																	
		Part 15																									8	8			16	16	30	30	26
	Job 2	Part 1																																	
		Part 2													5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	80	80	150	150	28
		Part 3																3	4	4	4	4	4	4	4	4					35	35	140	140	18
		Part 4																																	
		Part 5		5	5	5	5						5	5	5			3													38	38	120	120	21
		Part 6																															150	150	20
		Part 7																															120	120	14
		Part 8																																	
		Part 9			8	8		8	8	8																					40	40	80	80	8
		Part 10																																	
		Part 11	5	5		5	5	5	5	5	5			5			1	5	5	5		5									66	66	110	110	14
		Part 12																																	
		Part 13																															120	120	17
		Part 14	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3									60	60	180	180	20
		Part 15																																	
	Job 3	Part 1																															100	100	13
		Part 2																																	
		Part 3	4	4	4	4	4	4	4	4	4																				36	36	140	140	9
		Part 4			8				6		8	8	8	8	8																54	54	140	140	13
		Part 5																															60	60	24
		Part 6																																	
		Part 7																																	
		Part 8																															180	180	19
		Part 9																																	
		Part 10		16	16	16	16	16			16	14	16																		126	126	200	200	11
		Part 11																															50	50	13
		Part 12	16				16				16	16	11					9	16	16											116	116	150	150	18
		Part 13																																	
		Part 14																																	
		Part 15																8	8	8	2	8	8								42	42	120	120	21
	Job 4	Part 1					8	8	4																						20	20	110	110	8
		Part 2																															50	50	24
		Part 3																																	
		Part 4																	8	8	8					6					30	30	30	30	17
		Part 5																																	
		Part 6																															70	70	20
		Part 7																																	
		Part 8	8	8	8	8	8	8	8	8	8	8	8	8																	96	96	100	100	12
		Part 9	8	8			8				8	8	8	8	8	8	8	8	8	8	8									3	115	115	120	120	8
		Part 10																																	
		Part 11																					5	5	5	5	5	5	5	5	40	40	66	80	21
		Part 12						16							16	2	16														50	50	50	50	15
		Part 13																																	
		Part 14																					3								3	3	80	80	21
		Part 15																			6			8	8	8					30	30	60	60	24
	Job 5	Part 1																																	
		Part 2																																	
		Part 3												4	4	4	4	1									4	4	4	4	33	33	122	150	14
		Part 4																																	
		Part 5																															110	110	12
		Part 6																																	
		Part 7																																	
		Part 8																															40	40	17
		Part 9																															50	50	11
		Part 10																																	
		Part 11			5							5	5		5	5	4				5										34	34	130	130	14
		Part 12																																	
		Part 13																															120	120	27
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2																															20	20	8
		Part 3																																	
		Part 4																															150	150	10
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																															140	140	11
		Part 10																																	
		Part 11																																	
		Part 12																															110	110	15
		Part 13																																	

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
		Part 14																																	
		Part 15																																	
	Job 7	Part 1																															80	80	15
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																															140	140	17
		Part 6																																	
		Part 7																																	
		Part 8													8	8	8	8													32	32	150	150	16
		Part 9																																	
		Part 10																																	
		Part 11																															50	50	10
		Part 12																																	
		Part 13																																	
		Part 14																						3	3	3	3	3	3	3	21	21	70	70	24
		Part 15																																	
	Job 8	Part 1	8	8		8			4	8				8			6														50	50	50	50	15
		Part 2	5	5	5	5	5		5	5	4	5	5	5																	54	54	70	70	10
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																16				14									30	30	30	30	20
		Part 8																																	
		Part 9																					8	8	8	8	8				40	40	40	40	22
		Part 10																																	
		Part 11																																	
		Part 12		16		16			3				5	16		14															70	70	70	70	14
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																															24	150	15
		Part 4																															200	200	18
		Part 5																																	
		Part 6																															70	70	20
		Part 7																																	
		Part 8																															50	50	10
		Part 9																																	
		Part 10													16	16	16	12													60	60	60	60	16
		Part 11																																	
		Part 12																																	
		Part 13																															80	80	12
		Part 14																																	
		Part 15																															120	120	9
	Job 10	Part 1																															90	90	11
		Part 2																																	
		Part 3										4	4																		8	8	50	50	10
		Part 4	8	8		8	8	8	2	8																					50	50	100	100	8
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																				8						8	8	5	29	29	70	70	20
		Part 10																																	
		Part 11																																	
		Part 12																7													7	7	60	60	18
		Part 13																																	
		Part 14																																	
		Part 15	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8														120	120	200	200	15
Shop 2	Job 1	Part 1																																	
		Part 2	8	8	8	8	8		3	8	8																				59	59			
		Part 3																																	
		Part 4														6															6	6			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 2	Part 1																																	
		Part 2												8	6		8		8	8	8	8							8	8	70	70			
		Part 3																	5	5	5	5	5								25	25			
		Part 4																																	
		Part 5														2	8	8	4	8	8	8	8	8							62	62			
		Part 6			8	8	8	8		8	8	8	8	8			8	8		2											90	90			
		Part 7							16	16	16	16	16	16	16	8															120	120			
		Part 8																																	
		Part 9	5	5	5	5	5	5	5	5																					40	40			
		Part 10																																	
		Part 11																																	

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
		Part 12																																	
		Part 13								16	16	16	16	16			16	16	8												120	120			
		Part 14	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5									100	100			
		Part 15																																	
	Job 3	Part 1																																	
		Part 2																																	
		Part 3	5	5	2		5		5	5	5																				32	32			
		Part 4											16	16	16	10	16														74	74			
		Part 5																							8	8					16	16			
		Part 6																																	
		Part 7																																	
		Part 8																		8	8	8	8								32	32			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																	8	8	8	8	8								40	40			
	Job 4	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8	4																												4	4			
		Part 9									5																				5	5			
		Part 10																																	
		Part 11																									4	4	4	4	16	16			
		Part 12																																	
		Part 13																																	
		Part 14																					5								5	5			
		Part 15																						8	8	8					24	24			
	Job 5	Part 1																																	
		Part 2																																	
		Part 3												5	5	5	5	5						5	5	5	5	5	5	5	60	60			
		Part 4																																	
		Part 5	8	8	8	8	8	8	8	8	8	8	8	8	8	6															110	110			
		Part 6																																	
		Part 7																																	
		Part 8							8					8			8	8	8												40	40			
		Part 9										5	5	5	5	5	5	5	5	5	5										50	50			
		Part 10																																	
		Part 11	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4					96	96			
		Part 12																																	
		Part 13													16	16							16	16	16		8	16	16		120	120			
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2						8	5																						13	13			
		Part 3																																	
		Part 4	16			16		16	14	16	16	16																			110	110			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 7	Part 1												6	8	8	8														30	30			
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																	4												4	4			
		Part 6																																	
		Part 7																																	
		Part 8	4					8		6			8		8	8															42	42			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																						5	5	5	1				16	16			
		Part 15																																	
	Job 8	Part 1																																	
		Part 2										8	8																		16	16			
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																															
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4															16	16	16	16	16	16	16	16	16	16	16	16	8	200	200			
		Part 5																																	
		Part 6	8	8					8						8	8			8	6	8	8									70	70			
		Part 7																																	
		Part 8		8	8	8	8			2	8	8																			50	50			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13	16	16	16		16	16																							80	80			
		Part 14																																	
		Part 15	8	8	8	8	8	8	8	8	8																				72	72			
	Job 10	Part 1	8	8	8	8	8	8	8	8	8	8	8	2																	90	90			
		Part 2																																	
		Part 3			3	5		5				5	5																		23	23			
		Part 4		16	16		16		2																						50	50			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																				5	5	5	5	5	5	5	5	1	41	41			
		Part 10																																	
		Part 11																																	
		Part 12									16		16	16						5											53	53			
		Part 13																																	
		Part 14																																	
		Part 15										8	8	8	8	8	8	8													56	56			
Shop 3	Job 1	Part 1																16	16	16	16	16	16	16	16	16	6				150	150			
		Part 2	5	5	5	5	5	5	5	5	5	5	5																		55	55			
		Part 3																																	
		Part 4														4	4	4	4	4	4	4	4	4	4	4	4	4	4		56	56			
		Part 5																																	
		Part 6																																	
		Part 7	8	8	8	8	8	8		8	8			6																	70	70			
		Part 8	16	16		16			16			16		16	16					16	2										130	130			
		Part 9																																	
		Part 10																																	
		Part 11						4													4	8	6	8		8	8	8	8	8	70	70			
		Part 12																																	
		Part 13							8	8	8	8		8	8										1						49	49			
		Part 14																																	
		Part 15																								4	5	5			14	14			
	Job 2	Part 1																																	
		Part 2																																	
		Part 3																8	8	8	8	8	8	8	8	8	8				80	80			
		Part 4																																	
		Part 5																		8	8	4									20	20			
		Part 6															16	16	16			12									60	60			
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11														8	8	8	8	8	4										44	44			
		Part 12																																	
		Part 13																																	
		Part 14												5		5			5			5									20	20			
		Part 15																																	
	Job 3	Part 1							16	16	16	16	4	16	16																100	100			
		Part 2																																	
		Part 3	8	8	8	8	8	8	8	8	8																				72	72			
		Part 4											4	4	4																12	12			
		Part 5																				4	8	8	8	8	8				44	44			
		Part 6																																	
		Part 7																																	
		Part 8			16						16					16	4	16	16		14	16	16	16	2						148	148			
		Part 9																																	
		Part 10	16			16	16	16					10																		74	74			
		Part 11		8	8	8						2	8	8	8																50	50			
		Part 12								8							2	8	8	8											34	34			
		Part 13																																	
		Part 14																																	
		Part 15													3			5	5	5	5	5	5	5							38	38			
	Job 4	Part 1	16	16	16	16	16	10																							90	90			
		Part 2															5	5	5	5	5	5	5	5	5	5					50	50			
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6	16									6				16				16	16										70	70			
		Part 7																																	

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																					2		8						10	10			
		Part 12																																	
		Part 13																																	
		Part 14	5	5		5	5	5		5	5	5	5		5		5	2		5	5		5								72	72			
		Part 15																							5	1					6	6			
	Job 5	Part 1																																	
		Part 2																																	
		Part 3												5	8	8	8														29	29			
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2												5	2																7	7			
		Part 3																																	
		Part 4	4	4	4	4	4	4	4	4	4	4																			40	40			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	140	140			
		Part 10																																	
		Part 11																																	
		Part 12	8	8	8	8	8	8	8		8	8	8	8	8	8	6														110	110			
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 7	Part 1						6					12			16	16														50	50			
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8												136	136			
		Part 6																																	
		Part 7																																	
		Part 8					16	16		16			16				12														76	76			
		Part 9																																	
		Part 10																																	
		Part 11	8				8	4	8	8	8	6																			50	50			
		Part 12																																	
		Part 13																																	
		Part 14			5				5									3						5	5	5	5				33	33			
		Part 15																																	
	Job 8	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																										8	8	8	24	24			
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15	5	5	5	5	5	5	5	5	5	3																			48	48			
	Job 10	Part 1																																	
		Part 2																																	
		Part 3										8	8	3																	19	19			
		Part 4																																	
		Part 5																																	

Appendix 2 - Production Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																															
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15										2	5	5	2	5	5															24	24			

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**					
Shop 1	Job 1	Part 1																															150	150	24
		Part 2									6																				6	6	120	120	9
		Part 3																																	
		Part 4														8	8	8				8	8	8	8	2					58	58	120	120	14
		Part 5																																	
		Part 6																																	
		Part 7																															70	70	20
		Part 8																															130	130	19
		Part 9																																	
		Part 10										50																			50	50	50	50	10
		Part 11																															70	70	11
		Part 12								45																					45	45	45	45	8
		Part 13																															49	49	23
		Part 14																																	
		Part 15																										16			16	16	30	30	26
	Job 2	Part 1																																	
		Part 2															15													65	80	80	150	150	28
		Part 3																		11	4	4	4	4	4	4					35	35	140	140	18
		Part 4																																	
		Part 5													35								3								38	38	120	120	21
		Part 6																															150	150	20
		Part 7																															120	120	14
		Part 8																																	
		Part 9								40																					40	40	80	80	8
		Part 10																																	
		Part 11														45	1	5	5	5		5									66	66	110	110	14
		Part 12																																	
		Part 13																															120	120	17
		Part 14																48				12									60	60	180	180	20
		Part 15																																	
	Job 3	Part 1																															100	100	13
		Part 2																																	
		Part 3						24		8	4																				36	36	140	140	9
		Part 4											38		16																54	54	140	140	13
		Part 5																															60	60	24
		Part 6																																	
		Part 7																																	
		Part 8																															180	180	19
		Part 9																																	
		Part 10									96		30																		126	126	200	200	11
		Part 11																															50	50	13
		Part 12																		116											116	116	150	150	18
		Part 13																																	
		Part 14																																	
		Part 15																					42								42	42	120	120	21
	Job 4	Part 1							20																						20	20	110	110	8
		Part 2																															50	50	24
		Part 3																																	
		Part 4																	8	8	8					6					30	30	30	30	17
		Part 5																																	
		Part 6																															70	70	20
		Part 7																																	
		Part 8												96																	96	96	100	100	12
		Part 9							24		8	8	8	8	8	8	8	8	8	8	8									3	115	115	120	120	8
		Part 10																																	
		Part 11																					5	5	5	5	5	5	5	5	40	40	66	80	21
		Part 12															50														50	50	50	50	15
		Part 13																																	
		Part 14																					3								3	3	80	80	21
		Part 15																								30					30	30	60	60	24
	Job 5	Part 1																																	
		Part 2																																	
		Part 3														12	4	1									4	4	4	4	33	33	122	150	14
		Part 4																																	
		Part 5																															110	110	12
		Part 6																																	
		Part 7																																	
		Part 8																															40	40	17
		Part 9																															50	50	11
		Part 10																																	
		Part 11						5								20	4				5										34	34	130	130	14
		Part 12																																	
		Part 13																															120	120	27
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2																															20	20	8
		Part 3																																	
		Part 4																															150	150	10
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																															140	140	11
		Part 10																																	
		Part 11																																	
		Part 12																															110	110	15

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																															
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum delivered**	**Sum produced**	**Sum all shops**	**Demand qty**	**Due date**
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 7	Part 1																															80	80	15
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																															140	140	17
		Part 6																																	
		Part 7																																	
		Part 8																32													32	32	150	150	16
		Part 9																																	
		Part 10																																	
		Part 11																															50	50	10
		Part 12																																	
		Part 13																																	
		Part 14																							9	3	3	3	3	21	21	70	70	24
		Part 15																																	
	Job 8	Part 1															50														50	50	50	50	15
		Part 2		10			15		5			14	5	5																	54	54	70	70	10
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																				30									30	30	30	30	20
		Part 8																																	
		Part 9																						16	8	8	8				40	40	40	40	22
		Part 10																																	
		Part 11																																	
		Part 12														70															70	70	70	70	14
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																															24	150	15
		Part 4																															200	200	18
		Part 5																																	
		Part 6																															70	70	20
		Part 7																																	
		Part 8																															50	50	10
		Part 9																																	
		Part 10																60													60	60	60	60	16
		Part 11																																	
		Part 12																																	
		Part 13																															80	80	12
		Part 14																																	
		Part 15																															120	120	9
	Job 10	Part 1																															90	90	11
		Part 2																																	
		Part 3										4	4																		8	8	50	50	10
		Part 4								50																					50	50	100	100	8
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																				8						8	8	5	29	29	70	70	20
		Part 10																																	
		Part 11																																	
		Part 12																		7											7	7	60	60	18
		Part 13																																	
		Part 14																																	
		Part 15											88				32														120	120	200	200	15
Shop 2	Job 1	Part 1																																	
		Part 2	8						35		16																				59	59			
		Part 3																																	
		Part 4														6															6	6			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 2	Part 1																																	
		Part 2																												70	70	70			
		Part 3																		10	5	5	5								25	25			
		Part 4																																	
		Part 5																					54	8							62	62			
		Part 6												72								18									90	90			
		Part 7														120															120	120			
		Part 8																																	
		Part 9		10						30																					40	40			

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**date**
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																	120												120	120			
		Part 14																		90		10									100	100			
		Part 15																																	
	Job 3	Part 1																																	
		Part 2																																	
		Part 3	5	5		2					20																				32	32			
		Part 4													48	10	16														74	74			
		Part 5																								16					16	16			
		Part 6																																	
		Part 7																																	
		Part 8																			16	8	8								32	32			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																					40								40	40			
	Job 4	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8	4																												4	4			
		Part 9									5																				5	5			
		Part 10																																	
		Part 11																									4	4	4	4	16	16			
		Part 12																																	
		Part 13																																	
		Part 14																					5								5	5			
		Part 15																								24					24	24			
	Job 5	Part 1																																	
		Part 2																																	
		Part 3														15	5	5						5	5	5	5	5	5	5	60	60			
		Part 4																																	
		Part 5												96	8	6															110	110			
		Part 6																																	
		Part 7																																	
		Part 8																	40												40	40			
		Part 9											10	5	5	5	5	5	5	5	5										50	50			
		Part 10																																	
		Part 11	4		8			12								32	4	4	4	4	4	4	4	4	4	4					96	96			
		Part 12																																	
		Part 13																											120		120	120			
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2								13																					13	13			
		Part 3																																	
		Part 4										110																			110	110			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 7	Part 1															30														30	30			
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																	4												4	4			
		Part 6																																	
		Part 7																																	
		Part 8																42													42	42			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																								15	1				16	16			
		Part 15																																	
	Job 8	Part 1																																	
		Part 2										8	8																		16	16			
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**date**
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4																		48	16	16	16	16	16	16	16	16	16	8	200	200			
		Part 5																																	
		Part 6																				70									70	70			
		Part 7																																	
		Part 8										50																			50	50			
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13			48									32																	80	80			
		Part 14																																	
		Part 15			24				32		16																				72	72			
	Job 10	Part 1							56				32	2																	90	90			
		Part 2																																	
		Part 3							13			5	5																		23	23			
		Part 4								50																					50	50			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																				5	5	5	5	5	5	5	5	1	41	41			
		Part 10																																	
		Part 11																																	
		Part 12																		53											53	53			
		Part 13																																	
		Part 14																																	
		Part 15															48	8													56	56			
Shop 3	Job 1	Part 1																								144	6				150	150			
		Part 2	5							35	5	5	5																		55	55			
		Part 3																																	
		Part 4														4	4	4	4	4	4	4	4	4	4	4	4	4	4		56	56			
		Part 5																																	
		Part 6																																	
		Part 7					40															30									70	70			
		Part 8	16																		114										130	130			
		Part 9																																	
		Part 10																																	
		Part 11											4								4	8	6	8		8	8	8	8	8	70	70			
		Part 12																																	
		Part 13																							49						49	49			
		Part 14																																	
		Part 15																										14			14	14			
	Job 2	Part 1																																	
		Part 2																																	
		Part 3																		24	8	8	8	8	8	8	8				80	80			
		Part 4																																	
		Part 5																					20								20	20			
		Part 6																				60									60	60			
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11														8	8	8	8	8	4										44	44			
		Part 12																																	
		Part 13																																	
		Part 14													5							15									20	20			
		Part 15																																	
	Job 3	Part 1													100																100	100			
		Part 2																																	
		Part 3	8							56	8																				72	72			
		Part 4													12																12	12			
		Part 5																								36	8				44	44			
		Part 6																																	
		Part 7																																	
		Part 8										32									66	16	16	16	2						148	148			
		Part 9																																	
		Part 10					48						26																		74	74			
		Part 11													50																50	50			
		Part 12																		34											34	34			
		Part 13																																	
		Part 14																																	
		Part 15																					33	5							38	38			
	Job 4	Part 1					80			10																					90	90			
		Part 2																								50					50	50			
		Part 3																																	

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
Shop	Job	Part	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
		Part 4																																	
		Part 5																																	
		Part 6	16																			54									70	70			
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																					2		8						10	10			
		Part 12																																	
		Part 13																																	
		Part 14											45										27								72	72			
		Part 15																								6					6	6			
	Job 5	Part 1																																	
		Part 2																																	
		Part 3														21	8														29	29			
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 6	Part 1																																	
		Part 2												5	2																7	7			
		Part 3																																	
		Part 4		8								32																			40	40			
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9									45		10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	140	140			
		Part 10																																	
		Part 11																																	
		Part 12							56								54														110	110			
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 7	Part 1															50														50	50			
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5		16	8							56							56												136	136			
		Part 6																																	
		Part 7																																	
		Part 8																76													76	76			
		Part 9																																	
		Part 10																																	
		Part 11	8									42																			50	50			
		Part 12																																	
		Part 13																																	
		Part 14							10																	18	5				33	33			
		Part 15																																	
	Job 8	Part 1																																	
		Part 2																																	
		Part 3																																	
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15																																	
	Job 9	Part 1																																	
		Part 2																																	
		Part 3																										8	8	8	24	24			
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15								40	5	3																			48	48			

Appendix 3: Delivery Schedule for Single Scenario with Scenario 1

			Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**date**
	Job 10	Part 1																																	
		Part 2																																	
		Part 3										8	8	3																	19	19			
		Part 4																																	
		Part 5																																	
		Part 6																																	
		Part 7																																	
		Part 8																																	
		Part 9																																	
		Part 10																																	
		Part 11																																	
		Part 12																																	
		Part 13																																	
		Part 14																																	
		Part 15													14		10														24	24			

Appendix 4: Tardiness Quantity for Single Scenario with Scenario 1

		Day in the planning horizon																											
Job	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Job 1	Part 1																								6				
	Part 2									10	5																		
	Part 3																												
	Part 4														102	90	78	74	70	66	54	42	30	18	12	8	4		
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																												
	Part 10																												
	Part 11											66	66	66	66	66	66	66	66	62	54	48	40	40	32	24	16	8	
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 2	Part 1																												
	Part 2																												
	Part 3																		95	78	61	44	32	20	8				
	Part 4																												
	Part 5																					8							
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																												
	Part 10																												
	Part 11														57	48	35	22	9	5									
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 3	Part 1																												
	Part 2																												
	Part 3																												
	Part 4													26	16														
	Part 5																								8				
	Part 6																												
	Part 7																												
	Part 8																			66	42	18	2						
	Part 9																												
	Part 10																												
	Part 11																												
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																					5							
Job 4	Part 1																												
	Part 2																												
	Part 3																												
	Part 4																	22	14	6	6	6	6	6					
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9								96	83	75	67	59	51	43	35	27	19	11	3	3	3	3	3	3	3	3	3	
	Part 10																												
	Part 11																					73	68	55	50	41	32	23	14
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 5	Part 1																												
	Part 2																												
	Part 3														102	85	79	79	79	79	79	79	74	69	64	55	46	37	28
	Part 4																												
	Part 5												14	6															
	Part 6																												

Appendix 4: Tardiness Quantity for Single Scenario with Scenario 1

		Day in the planning horizon																											
Job	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
	Part 7																												
	Part 8																												
	Part 9											40	35	30	25	20	15	10	5										
	Part 10																												
	Part 11														49	41	37	33	29	20	16	12	8	4					
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 6	Part 1																												
	Part 2								7	7	7	7	2																
	Part 3																												
	Part 4																												
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9											85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	
	Part 10																												
	Part 11																												
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 7	Part 1																												
	Part 2																												
	Part 3																												
	Part 4																												
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																												
	Part 10																												
	Part 11																												
	Part 12																												
	Part 13																												
	Part 14																							18	9	6	3	
	Part 15																												
Job 8	Part 1																												
	Part 2										18	5																	
	Part 3																												
	Part 4																												
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																					24	16	8					
	Part 10																												
	Part 11																												
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15																												
Job 9	Part 1																												
	Part 2																												
	Part 3															150	150	150	150	150	150	150	150	150	150	150	142	134	126
	Part 4																		152	136	120	104	88	72	56	40	24	8	
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																												
	Part 10																												
	Part 11																												
	Part 12																												

Appendix 4: Tardiness Quantity for Single Scenario with Scenario 1

		Day in the planning horizon																											
Job	**Part**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
	Part 13																												
	Part 14																												
	Part 15									3																			
Job 10	Part 1											2																	
	Part 2																												
	Part 3										20	3																	
	Part 4																												
	Part 5																												
	Part 6																												
	Part 7																												
	Part 8																												
	Part 9																				57	52	47	42	37	32	19	6	
	Part 10																												
	Part 11																												
	Part 12																												
	Part 13																												
	Part 14																												
	Part 15															8													

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
Shop 1	Job 1	Part 1	Sc 1																															150	150	24
			Sc 2																															150	150	27
			Sc 3																															150	150	21
			Sc 4																															150	150	21
		Part 2	Sc 1									5																				6	6	120	120	9
			Sc 2					1																								1	1	120	120	12
			Sc 3																													1	1	120	120	8
			Sc 4								5	5																				11	11	120	120	8
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1														8	8	8	8	8			8	8	2						64	64	120	120	14
			Sc 2						6									8	8	8	8		8		2							48	48	120	120	17
			Sc 3								8	8	8	8	8				8		8		8	8		2						80	80	120	120	11
			Sc 4								8	8	8	8	8		8				2	8			8	8						80	80	120	120	11
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 8	Sc 1																															130	130	19
			Sc 2																															130	130	19
			Sc 3																															130	130	19
			Sc 4																	8	8	8										24	24	130	130	19
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1								16	16	16																			50	50	50	50	10
			Sc 2		2						16	16	16																			50	50	50	50	10
			Sc 3									16	16																			34	34	50	50	10
			Sc 4									16	16																			34	34	50	50	10
		Part 11	Sc 1																															70	70	11
			Sc 2																															70	70	11
			Sc 3																															70	70	11
			Sc 4																															70	70	11
		Part 12	Sc 1								16																					45	45	45	45	8
			Sc 2	13						16	16																					45	45	45	45	8
			Sc 3								16																					45	45	45	45	8
			Sc 4								16																					45	45	45	45	8
		Part 13	Sc 1																															49	49	23
			Sc 2																															49	49	23
			Sc 3																															49	49	23
			Sc 4																															49	49	23
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																									8	8			16	16	30	30	26
			Sc 2																															30	30	26
			Sc 3																								4	8	8			20	20	30	30	26
			Sc 4																								4	8	8			20	20	30	30	26
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1													5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	80	80	150	150	28
			Sc 2											5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	90	90	150	150	28
			Sc 3												3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	83	83	150	150	28
			Sc 4														5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	75	75	150	150	28
		Part 3	Sc 1																3	4	4	4	4	4	4	4	4					35	35	140	140	18
			Sc 2												4	4	4	4	4	4	4	4	4	4								40	40	140	140	18
			Sc 3																4	4	4	4	4	4	4	4	3					35	35	140	140	18
			Sc 4																4	4	4	4	4	4	4	4	3					35	35	140	140	18
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1										5			5	5							3								32	32	120	120	21
			Sc 2			5		4		5		5	5																			24	24	120	120	24
			Sc 3										4	5	5	5	5	5	5	5	5											58	58	120	120	18
			Sc 4										5	5	5	5	5	5	5	5	4											58	58	120	120	18
		Part 6	Sc 1																															150	150	20
			Sc 2																															150	150	23
			Sc 3																															150	150	17
			Sc 4																															150	150	17
		Part 7	Sc 1																															120	120	14
			Sc 2																															120	120	17
			Sc 3																															120	120	11
			Sc 4																															120	120	11
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 5: Production Schedule - All Scenarios

Shop	Job	Part	Scenario	Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 4																																	
		Part 9	Sc 1	8		8	8	8	8																							40	40	80	80	8
			Sc 2																													40	40	80	80	8
			Sc 3																													40	40	80	80	8
			Sc 4																													40	40	80	80	8
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1	5						5	5	5	5	5	5	5	5	5	5	5		5	1									66	66	110	110	14
			Sc 2								5	5	5	5	5	5	5	5	5		5	5	5									70	70	110	110	14
			Sc 3											5	1	5	5	5	5		5	5	5									51	51	110	110	14
			Sc 4											5	5	5	5	5	5	5		1	5									51	51	110	110	14
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															120	120	17
			Sc 2																															120	120	17
			Sc 3																															120	120	17
			Sc 4																															120	120	17
		Part 14	Sc 1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3									60	60	180	180	20
			Sc 2								3	3	3	3	3	3	3	3	3	3	3	3	3									60	60	180	180	20
			Sc 3								3	3	3	3	3	3	3	3	3	3	3	3	3									60	60	180	180	20
			Sc 4								3	3	3	3	3	3	3	3	3	3	3	3	3									60	60	180	180	20
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1																															100	100	13
			Sc 2																															100	100	13
			Sc 3																															100	100	13
			Sc 4																															100	100	13
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1	4	4	4	4	4	4	4	4	4																				36	36	140	140	9
			Sc 2								4	4																				36	36	140	140	9
			Sc 3								4	4																				36	36	140	140	9
			Sc 4								4	4																				36	36	140	140	9
		Part 4	Sc 1								8	8	8	8	8	8																48	48	140	140	13
			Sc 2								8	8	8	8	8	8	8															56	56	140	140	13
			Sc 3													8	8	8														24	24	140	140	13
			Sc 4													8		8	8													24	24	140	140	13
		Part 5	Sc 1																															60	60	24
			Sc 2																															60	60	24
			Sc 3																															60	60	24
			Sc 4																															60	60	24
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															180	180	19
			Sc 2																															180	180	22
			Sc 3																															180	180	19
			Sc 4																															180	180	16
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1	16	14	16	16	16	16	16				16																		126	126	200	200	11
			Sc 2												16	16																142	142	200	200	14
			Sc 3								16																					126	126	200	200	8
			Sc 4								16																					126	126	200	200	8
		Part 11	Sc 1																															50	50	13
			Sc 2																															50	50	16
			Sc 3																															50	50	10
			Sc 4																															50	50	10
		Part 12	Sc 1		16		16		16				16			11			16	9	16											116	116	150	150	18
			Sc 2									16			16		9	16			11											116	116	150	150	18
			Sc 3										16	11																		75	75	150	150	15
			Sc 4													11		16	9	16	16											116	116	150	150	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																8	8	8	8	8	2								42	42	120	120	21
			Sc 2																8	8	8	8	7	8								47	47	120	120	21
			Sc 3																							8	4					12	12	120	120	21
			Sc 4																							8	4					12	12	120	120	21
	Job 4	Part 1	Sc 1			8	4		8	8																						28	28	110	110	8
			Sc 2																													28	28	110	110	8

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	produced	delivered	shops	qty	date
			Sc 3								6																					34	34	110	110	8
			Sc 4								6																					34	34	110	110	8
		Part 2	Sc 1																															50	50	24
			Sc 2																															50	50	24
			Sc 3																															50	50	24
			Sc 4																															50	50	24
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																			8	8			6	8					30	30	30	30	17
			Sc 2																			8		8	6	8						30	30	30	30	17
			Sc 3																	8		8			8	6						30	30	30	30	17
			Sc 4																	8	6		8	8								30	30	30	30	17
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1								8	8	8	8	8																	96	96	100	100	12
			Sc 2	8	8	8	8	8	8	8		2	8	8	8																	82	82	100	100	12
			Sc 3								8	8	8	8	8																	96	96	100	100	12
			Sc 4								8	8	8	8	8																	96	96	100	100	12
		Part 9	Sc 1								8	8	8	8	8	8	8	8	8	8	8	8									3	115	115	120	120	8
			Sc 2		8					8	8	8	8	8	8	8	8	8	8	8	8	8										112	112	120	120	8
			Sc 3								8	8	8	8	8	8	8	8	8	8	8	8							7			119	119	120	120	8
			Sc 4								8	8	8	8	8	8	8		8	8	8	8									1	105	105	120	120	8
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 2																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 3																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 4																					5	5	5	5	5	5	5	5	40	40	66	80	21
		Part 12	Sc 1											16	15			16														50	50	50	50	15
			Sc 2	3										16					10	16	5											50	50	50	50	18
			Sc 3													15	16	16														50	50	50	50	15
			Sc 4										16	15	16																	50	50	50	50	12
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																					3								3	3	80	80	21
			Sc 2																					3	3	3	3	3	3	3	3	24	24	80	80	24
			Sc 3																															80	80	18
			Sc 4																															80	80	18
		Part 15	Sc 1																					6	8	8	8					30	30	60	60	24
			Sc 2																				1		8	8	8	8	8	8		49	49	60	60	27
			Sc 3																8	8	8	8	8	8	8							56	56	60	60	21
			Sc 4								8		5									8	8	8	8							45	45	60	60	21
	Job 5	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1												4	4	4	4	1									4	4	4	4	33	33	122	150	14
			Sc 2																						4	4	4	4	4	4	4	28	28	122	150	17
			Sc 3											4	4	4	4	4									1	4	4	4	4	37	37	122	150	11
			Sc 4											4	4	4	4	4									1	4	4	4	4	37	37	122	150	11
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																													6	6	110	110	12
			Sc 2				5	1																								6	6	110	110	15
			Sc 3								5	5																				16	16	110	110	9
			Sc 4								5	5																				16	16	110	110	8
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															40	40	17
			Sc 2																															40	40	20
			Sc 3																															40	40	14
			Sc 4																															40	40	14
		Part 9	Sc 1																															50	50	11

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	produced	delivered	shops	qty	date
			Sc 2																															50	50	11
			Sc 3																															50	50	11
			Sc 4															8													2	10	10	50	50	11
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																		5		4									34	34	130	130	14
			Sc 2		5	5	5	5	5											5												30	30	130	130	14
			Sc 3												4					5												34	34	130	130	14
			Sc 4																		5	4										34	34	130	130	14
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															120	120	27
			Sc 2																															120	120	27
			Sc 3																															120	120	27
			Sc 4																															120	120	27
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																															20	20	8
			Sc 2																															20	20	11
			Sc 3																															20	20	8
			Sc 4																															20	20	8
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																															150	150	10
			Sc 2																															150	150	13
			Sc 3																															150	150	10
			Sc 4																															150	150	10
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																															140	140	11
			Sc 2																															140	140	11
			Sc 3																															140	140	8
			Sc 4																															140	140	14
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																															110	110	15
			Sc 2																															110	110	15
			Sc 3																															110	110	12
			Sc 4																															110	110	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1																															80	80	15
			Sc 2																															80	80	15
			Sc 3									8	8	8	6																	30	30	80	80	12
			Sc 4																															80	80	18

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																															140	140	17
			Sc 2																															140	140	17
			Sc 3																															140	140	17
			Sc 4																															140	140	17
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1													8	8	8	8													32	32	150	150	16
			Sc 2																															150	150	19
			Sc 3													8	8	8	8													32	32	150	150	16
			Sc 4													8	8	8	8													32	32	150	150	16
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																															50	50	10
			Sc 2																															50	50	13
			Sc 3								5	5	5																			15	15	50	50	10
			Sc 4								5	5	5																			15	15	50	50	10
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																						3	3	3	3	3	3	3	21	21	70	70	24
			Sc 2																															70	70	24
			Sc 3																					3	3	3	3	3	3	3	3	24	24	70	70	21
			Sc 4																					3	3	3	3	3	3	3	3	24	24	70	70	27
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1										8	8	8	8		8														48	48	50	50	15
			Sc 2				4	4																								8	8	50	50	18
			Sc 3												2	8	8	8														34	34	50	50	15
			Sc 4								2	8	8		8	8	8															50	50	50	50	15
		Part 2	Sc 1								5		5	5	5																	54	54	70	70	10
			Sc 2	5	5	5	5	4	5	5	5	5	5																			49	49	70	70	10
			Sc 3								5	5	5	5	2																	56	56	70	70	8
			Sc 4										5	5	5	5																54	54	70	70	13
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																16				14									30	30	30	30	20
			Sc 2															16					14									30	30	30	30	20
			Sc 3											16						14												30	30	30	30	17
			Sc 4												16											14						30	30	30	30	23
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																					8	8	8	8	8				40	40	40	40	22
			Sc 2																				8	8	8	8	8					40	40	40	40	22
			Sc 3																					8	8	8	8	8				40	40	40	40	22

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	produced	delivered	shops	qty	date
			Sc 4																					8	8	8	8	8				40	40	40	40	22
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1									16			1	5	16															70	70	70	70	14
			Sc 2			16		16					16			16			6													70	70	70	70	17
			Sc 3									16		5	16	1																70	70	70	70	14
			Sc 4									16		1		5	16															70	70	70	70	14
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 9	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																															24	150	15
			Sc 2																															24	150	18
			Sc 3																															24	150	15
			Sc 4																															24	150	15
		Part 4	Sc 1																															200	200	18
			Sc 2																															200	200	21
			Sc 3																															200	200	18
			Sc 4																															200	200	18
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															50	50	10
			Sc 2																															50	50	10
			Sc 3																															50	50	10
			Sc 4																															50	50	10
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1												16		12	16	16													60	60	60	60	16
			Sc 2											16			16	16	12													60	60	60	60	16
			Sc 3											16	16	16																48	48	60	60	13
			Sc 4														16	16		16		12										60	60	60	60	19
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															80	80	12
			Sc 2																															80	80	12
			Sc 3																															80	80	9
			Sc 4																															80	80	15
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																															120	120	9
			Sc 2																															120	120	9
			Sc 3																															120	120	9
			Sc 4																															120	120	9
	Job 10	Part 1	Sc 1																															90	90	11
			Sc 2																															90	90	11
			Sc 3								2																					2	2	90	90	8
			Sc 4																															90	90	14
		Part 2	Sc 1																																	
			Sc 2																																	

Appendix 5: Production Schedule - All Scenarios

Shop	Job	Part	Scenario	Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1										4	4																		8	8	50	50	10
			Sc 2										4	4																		8	8	50	50	10
			Sc 3										4																			4	4	50	50	10
			Sc 4										4																			4	4	50	50	10
		Part 4	Sc 1	8	8	8	8	8	2	8																						50	50	100	100	8
			Sc 2																													50	50	100	100	8
			Sc 3																													50	50	100	100	8
			Sc 4																													50	50	100	100	8
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																				8						8	8	5	29	29	70	70	20
			Sc 2																									8	8	8	8	32	32	70	70	23
			Sc 3																				8						1	8	8	25	25	70	70	20
			Sc 4																				8						8	8	5	29	29	70	70	20
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																	7												7	7	60	60	18
			Sc 2														7					16	16	16								55	55	60	60	21
			Sc 3																16	16	16											48	48	60	60	18
			Sc 4																7													7	7	60	60	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8														120	120	200	200	15
			Sc 2								8	8	8	8	8	8	8	8														120	120	200	200	15
			Sc 3								8	8	8	8	8	8	8	8														120	120	200	200	12
			Sc 4									8	3	8	8	8	8	8	8	8	8											131	131	200	200	18
Shop 2	Job 1	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																	8												8	8			
			Sc 4																																	
		Part 2	Sc 1	8	8	8	8	8	8	8		8																				64	64			
			Sc 2												7																	63	63			
			Sc 3								8	2																				66	66			
			Sc 4								8																					64	64			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2															12	16	16	4											48	48			
			Sc 3											16	16																	32	32			
			Sc 4											16	16																	32	32			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																	2	8	8	8									26	26			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																							5						5	5			
			Sc 3																																	
			Sc 4																																	
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1															8	8	8	8	8	8		8					6	8	70	70			
			Sc 2																		8	8	8	8	8				4	8	8	60	60			
			Sc 3												8	8				8	8	8		8					3	8	8	67	67			
			Sc 4																8	8	8	8	8	8	8				3	8	8	75	75			
		Part 3	Sc 1																	5	5	5	5	5								25	25			
			Sc 2																		5	2										7	7			
			Sc 3																	5	5	5	5	5								25	25			
			Sc 4																	5	5	5	5	5								25	25			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1														8	8	8	4	8	8	8	8	8							68	68			
			Sc 2								8				4				8	8	8	8	8	8	8	8	8	8				92	92			
			Sc 3												2	8	8	8	8	4	8	8										54	54			
			Sc 4												2	8	8	8	8	4	8	8										54	54			
		Part 6	Sc 1	8	8	8	8	8		8		8	8			8		8	8				2									90	90			
			Sc 2								8			8	8			8		8	2			8	8	8						114	114			
			Sc 3								8		8			8	8	8	2													90	90			
			Sc 4										8		8	8	8	8	2													90	90			
		Part 7	Sc 1	16	16	16	16	16			16					16	8															120	120			
			Sc 2								16				16					8												120	120			
			Sc 3								16		16	8																		120	120			
			Sc 4									16	16	8																		120	120			
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1	5	5	5	5	5	5	5	5																					40	40			
			Sc 2								5																					40	40			
			Sc 3								5																					40	40			
			Sc 4								5																					40	40			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1									16		16	16	8	16	16	16	16												120	120			
			Sc 2								16	16	16			16	16	16	8	16												120	120			
			Sc 3										16	16	16	16	16	8	16	16												120	120			
			Sc 4								16	16	16	16	16	16			8	16												120	120			
		Part 14	Sc 1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5									100	100			
			Sc 2								5	5	5	5	5	5	5	5	5	5	5	5	5									100	100			
			Sc 3								5	5	5	5	5	5	5	5	5	5	5	5	5									100	100			
			Sc 4								5	5	5	5	5	5	5	5	5	5	5	5	5									100	100			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3													8																8	8			
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
		Part 3	Sc 1	5	5	5			5	5	5	2																				32	32			
			Sc 2								5	2																				32	32			
			Sc 3								2	5																				32	32			
			Sc 4								2	5																				32	32			
		Part 4	Sc 1											16	16	16	16	16														80	80			
			Sc 2								14				16	6	16	4														56	56			
			Sc 3													16	16	16	8													56	56			
			Sc 4													16	16	16	8													56	56			
		Part 5	Sc 1																							8	8					16	16			
			Sc 2																																	
			Sc 3																							4						4	4			
			Sc 4																						4							4	4			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																		8	8	8	8								32	32			
			Sc 2																					8	8	8						24	24			
			Sc 3																	8	8	8	8	8								40	40			
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3															1														1	1			
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																	8	8	8	8	8								40	40			
			Sc 2																	8	8	8	8	8								40	40			
			Sc 3																	8	8	8	8	4	8	8	8					60	60			
			Sc 4																			8	1		8	8	8					33	33			
	Job 4	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1												4																	4	4			
			Sc 2											2																		2	2			
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1									5																				5	5			
			Sc 2									5																				5	5			
			Sc 3									1																				1	1			
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 4																																	
		Part 11	Sc 1																									4	4	4	4	16	16			
			Sc 2																										4	4	4	12	12			
			Sc 3																									4	4	4	4	16	16			
			Sc 4																									4	4	4	4	16	16			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																					5								5	5			
			Sc 2																									1				1	1			
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																						8	8	8					24	24			
			Sc 2																									6				6	6			
			Sc 3																					4								4	4			
			Sc 4																				7	8								15	15			
	Job 5	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1												5	5	5	5	5						5	5	5	5	5	5	5	60	60			
			Sc 2												5	5	5	5	5	5		3	5	5	5	5	5	5	5	5	5	78	78			
			Sc 3											5	5	5	5	5	5						5	5	5	5	5	5	5	65	65			
			Sc 4											5	5	5	5	5	5						5	5	5	5	5	5	5	65	65			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1								8	8	8	8	8	8																104	104			
			Sc 2	8	8	8	8	8	8	8		8	8	8	4	8	4	8														104	104			
			Sc 3								8	8	8	8	6																	94	94			
			Sc 4								8	8	8	8	6																	94	94			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1															8	8	8												40	40			
			Sc 2			8				8	6			6				4					8									40	40			
			Sc 3										6		2	8	8															40	40			
			Sc 4											8		8	8															40	40			
		Part 9	Sc 1										5	5	5	5	5	5	5	5	5	5										50	50			
			Sc 2										5	5		5	5	5	5	5	5	5	5									50	50			
			Sc 3										5	5	5	5	5	5	5	5	5	5										50	50			
			Sc 4									5	5	5	5	5				5	5	5										40	40			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1								4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4					96	96			
			Sc 2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4				100	100			
			Sc 3								4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4					96	96			
			Sc 4								4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4					96	96			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																			16	16	16						8		120	120			
			Sc 2	16	16	16				16									8			16	16	16								120	120			
			Sc 3																		16	16							8	16		120	120			
			Sc 4																8				16	16						16		120	120			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1								8																					8	8			
			Sc 2										3	8																		11	11			
			Sc 3											8																		8	8			
			Sc 4									8	2																			10	10			
		Part 3	Sc 1																																	
			Sc 2																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1								14	16	16																			110	110			
			Sc 2		16	16		16	16			16	16	16		10																122	122			
			Sc 3								14	16	16																			110	110			
			Sc 4								14	16	16																			110	110			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2												5																	5	5			
			Sc 3									4																				4	4			
			Sc 4														5	5	5													15	15			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3								16	16		16	16																	64	64			
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
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			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1												6	8	8	8														30	30			
			Sc 2												6	8		8														22	22			
			Sc 3										8	8	8																	24	24			
			Sc 4									8			8		6	8	8	8	8											54	54			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																																	
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			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																	4												4	4			
			Sc 2														4															4	4			
			Sc 3																	4												4	4			
			Sc 4																	4												4	4			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1										6	8	4	8	8															42	42			
			Sc 2					8							8	8	8	4	8	8	8	8										68	68			
			Sc 3											8	6			8	8													38	38			
			Sc 4										6		8			8	8	6												44	44			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																						5	5	5	1				16	16			
			Sc 2																					5	5	5	5					20	20			
			Sc 3																					5	5	5	5	1				21	21			
			Sc 4																									1	5	5		11	11			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3														8	8														16	16			
			Sc 4																																	
		Part 2	Sc 1										8	8																		16	16			
			Sc 2								8	8	5																			21	21			
			Sc 3									6	8																			14	14			
			Sc 4													6																6	6			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
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		Part 5	Sc 1																																	
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			Sc 4																																	
		Part 6	Sc 1																																	
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			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 8	Sc 1																																	
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		Part 9	Sc 1																																	
			Sc 2																																	
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		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
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		Part 12	Sc 1																																	
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		Part 13	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 9	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
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		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
		Part 4	Sc 1																16	16	16	16	16	16	16	16	16	16	16	16	8	200	200			
			Sc 2																		12	16	16	16	16	16	16	16	16	16	16	172	172			
			Sc 3																8	16	16	16	16	16	16	16	16	16	16	16	16	200	200			
			Sc 4																8	16	16	16	16	16	16	16	16	16	16	16	16	200	200			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1								8			8	8		8			8	8	8	6									70	70			
			Sc 2						8			8	8			8	8		8		6	8	8									70	70			
			Sc 3									8		8	8				6	8	8	8	8									70	70			
			Sc 4								8	8		8					6	8	8	8	8									70	70			
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1								8	8	2																			50	50			
			Sc 2	8	8		8		8		2	8	8																			50	50			
			Sc 3								8	8	2																			50	50			
			Sc 4								8	8	2																			50	50			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3												8	4																12	12			
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1								16		16																			80	80			
			Sc 2				16	16	16					16	16																	80	80			
			Sc 3								16	16																				80	80			
			Sc 4														16	16														80	80			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1								8	8																				72	72			
			Sc 2	8	8	8	8	8	8	8	8	8																				72	72			
			Sc 3								8	8																				72	72			
			Sc 4								8	8	3																			75	75			
	Job 1(	Part 1	Sc 1								8	8	8	8	2																	90	90			
			Sc 2	8	8	8	8	8	8	8	8	8	8	8	2																	90	90			
			Sc 3								8	8																				72	72			
			Sc 4								8		8	8		8	2															90	90			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1									3	5	5																		23	23			
			Sc 2				5	5				3	5	5																		23	23			
			Sc 3								3		5																			18	18			
			Sc 4								3		5																			18	18			
		Part 4	Sc 1								2																					50	50			
			Sc 2	16			16			16	2																					50	50			
			Sc 3								2																					50	50			
			Sc 4								2																					50	50			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																				5	5	5	5	5	5	5	5	1	41	41			
			Sc 2																					5	5	5	5	5	5	5	3	38	38			
			Sc 3																				5	5	5	5	5	5	5	5	5	45	45			
			Sc 4																				5	5	5	5	5	5	5	5	1	41	41			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 5: Production Schedule - All Scenarios

Shop	Job	Part	Scenario	Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 4																																	
		Part 12	Sc 1												16	16	16				5											53	53			
			Sc 2																					5								5	5			
			Sc 3																		12											12	12			
			Sc 4														16		5	16	16											53	53			
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1										8	8	8	8	8	8	8													56	56			
			Sc 2										8	8	8	8	8	8	8													56	56			
			Sc 3										8	8	8	8	8	8	8													56	56			
			Sc 4										5	8	8	8	8	8	8	8	8											69	69			
Shop 3	Job 1	Part 1	Sc 1															6	16	16	16	16	16	16	16	16	16					150	150			
			Sc 2																		6	16	16	16	16	16	16	16	16	16		150	150			
			Sc 3														14	16	16	16	16	16	16	16	16							142	142			
			Sc 4													16	16	6	16	16	16	16	16	16	16							150	150			
		Part 2	Sc 1	5	5	5	5	5	5	5		5	5	5																		50	50			
			Sc 2									5	5	1	5	5																56	56			
			Sc 3								5	5	5	3																		53	53			
			Sc 4								5	5																				45	45			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1														4	4	4	4	4	4	4	4	4	4	4	4	4	4		56	56			
			Sc 2															4	4	4	4	4	4									24	24			
			Sc 3											4	4																	8	8			
			Sc 4											4	4																	8	8			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1		8	8				8				8		8	8			8	8		6									70	70			
			Sc 2								8	8		8			8	8	6													70	70			
			Sc 3								8	8	8	8	8								6									70	70			
			Sc 4								8	8	8					8	8	6												70	70			
		Part 8	Sc 1									16	16		16		16	2	16	16	16	16										130	130			
			Sc 2								16	16			16		4	16	16	16	16	14										130	130			
			Sc 3								16	16	16	16				2	16	16	16	16										130	130			
			Sc 4																	16	16	16	16	16								80	80			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3										16																			16	16			
			Sc 4										16																			16	16			
		Part 11	Sc 1											4								4	8	8	8		8	6	8	8	8	70	70			
			Sc 2								8		8	4										8		8	8	2	8	8	8	70	70			
			Sc 3											3								5	8	8	6	8	8		8	8	8	70	70			
			Sc 4											3								5	8	8	8	8		8	6	8	8	70	70			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1											8	8	8	8	8				8				1						49	49			
			Sc 2													8	8		8	8	8	8				1						49	49			
			Sc 3								8	8	8			8								1	8	8						49	49			
			Sc 4									8	8	8	8			8	8							1						49	49			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																								4	5	5			14	14			
			Sc 2																						5	5	5	5	5			25	25			
			Sc 3																									5	5			10	10			
			Sc 4																									5	5			10	10			
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																8	8	8	8	8	8	8	8	8	8				80	80			
			Sc 2												5	8	8	8	8	8	8	8	8	8	8	8						93	93			
			Sc 3																8	8	8	8	8	8	8	8	8	8				80	80			
			Sc 4																8	8	8	8	8	8	8	8	8	8				80	80			
		Part 4	Sc 1																																	
			Sc 2																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																								Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																		8	8		4								20	20			
			Sc 2																								4					4	4			
			Sc 3																		8											8	8			
			Sc 4																		8											8	8			
		Part 6	Sc 1		16	16												16	12													60	60			
			Sc 2																							4						36	36			
			Sc 3								16									12												60	60			
			Sc 4											16						12												60	60			
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1														8	8	8	8	8	4										44	44			
			Sc 2													8	8				8	8	8									40	40			
			Sc 3												8	8	8	8	8	8	8	3										59	59			
			Sc 4												8	8	8	8	8	8	8	3										59	59			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																	5	5		5									20	20			
			Sc 2						5					5	5								5									20	20			
			Sc 3														5					5	5									20	20			
			Sc 4																		5	5	5									20	20			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1	4	16					16	10	16	16	16	6																	100	100			
			Sc 2								10	16	16	16		6																100	100			
			Sc 3									16	16		6	16	2															92	92			
			Sc 4									16	16	16	16																	100	100			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1	8	8	8	8	8	8	8	8	8																				72	72			
			Sc 2								8	8																				72	72			
			Sc 3								8	8																				72	72			
			Sc 4								8	8																				72	72			
		Part 4	Sc 1											4	4	4																12	12			
			Sc 2								4	4	4	4	4	4	4															28	28			
			Sc 3													4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		60	60			
			Sc 4													4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		60	60			
		Part 5	Sc 1																				8	4	8	8	8	8				44	44			
			Sc 2																		8	8	8	8	8	8	4	8				60	60			
			Sc 3																			8	8	8	8	8	8	8				56	56			
			Sc 4																			8	8	8	8	8	8	8				56	56			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1	16		16		16	10		16			16				8					16	16	16	2						148	148			
			Sc 2													16						2	16	16	16	16	16					156	156			
			Sc 3													16	16						16	16	16	2						140	140			
			Sc 4								16	16	16	16	12	16	16	12							2							180	180			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1				16	16	16	10				16																		74	74			
			Sc 2																													58	58			
			Sc 3								16																					74	74			
			Sc 4								16																					74	74			
		Part 11	Sc 1		2		8		8	8			4	4	8	8																50	50			
			Sc 2															8	8	8												50	50			
			Sc 3								8	8	8																			50	50			
			Sc 4								8	8	8																			50	50			
		Part 12	Sc 1																8	8	8											34	34			

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum produced**	**Sum delivered**	**Sum all shops**	**Demand qty**	**Due date**
			Sc 2			8			2										8	8	8											34	34			
			Sc 3								8	8	8	8	8	8	8	8														74	74			
			Sc 4								8				8			8														34	34			
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1										2		1				5	5	5	5	5	5	5							38	38			
			Sc 2													3			5	5	5	5	5	5								33	33			
			Sc 3															3	5	5	5	5	5	5	5	5	5					48	48			
			Sc 4										5	5	5	5	5	5	5	5	5	5	5	5	5	5	5					75	75			
	Job 4	Part 1	Sc 1								6																					82	82			
			Sc 2	12		16	16	16	16		6																					82	82			
			Sc 3																													76	76			
			Sc 4																													76	76			
		Part 2	Sc 1															5	5	5	5	5	5	5	5	5	5					50	50			
			Sc 2															5	5	5	5	5	5	5	5	5	5					50	50			
			Sc 3														5	5	5	5	5	5	5	5		5	5					50	50			
			Sc 4															5	5	5	5	5	5	5	5	5	5					50	50			
		Part 3	Sc 1																																	
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		Part 4	Sc 1																																	
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		Part 5	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1								16	16	16				16						6									70	70			
			Sc 2											16		16	16	16					6									70	70			
			Sc 3									16	16				16					6	16									70	70			
			Sc 4													16	16	16				6	16									70	70			
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2											16																		16	16			
			Sc 3												4																	4	4			
			Sc 4												4																	4	4			
		Part 9	Sc 1																																	
			Sc 2								3																					3	3			
			Sc 3																																	
			Sc 4								5	5	5																			15	15			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																							8		2				10	10			
			Sc 2																						8			6				14	14			
			Sc 3																						2			8				10	10			
			Sc 4																								8		2			10	10			
		Part 12	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 13	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1									5	5	5	5		5	5	5			5		2								72	72			
			Sc 2	5	5	5	5	5		5	5	5					5	5						5								55	55			
			Sc 3								5	5	5	5	5	5		5	5	5	5											80	80			
			Sc 4								5	5	5	5	5	5	5	5	5	5												80	80			
		Part 15	Sc 1																							5	1					6	6			
			Sc 2																											5		5	5			
			Sc 3																																	
			Sc 4																																	
	Job 5	Part 1	Sc 1																																	
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			Sc 4																																	
		Part 3	Sc 1												5	8	8	8														29	29			
			Sc 2																								8	8				16	16			
			Sc 3													4	8	8														20	20			
			Sc 4													4	8	8														20	20			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	produced	delivered	shops	qty	date
		Part 5	Sc 1																																	
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			Sc 4																																	
		Part 6	Sc 1																																	
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		Part 7	Sc 1																																	
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		Part 9	Sc 1																																	
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		Part 10	Sc 1																																	
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		Part 11	Sc 1																																	
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		Part 12	Sc 1																																	
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		Part 13	Sc 1																																	
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			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1								5				5	2																12	12			
			Sc 2								5			4																		9	9			
			Sc 3											2	5	5																12	12			
			Sc 4										5	5																		10	10			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1								4	4	4																			40	40			
			Sc 2	4	4	4	4	4	4	4																						28	28			
			Sc 3								4	4	4																			40	40			
			Sc 4								4	4	4																			40	40			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
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		Part 6	Sc 1																																	
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		Part 7	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1								5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	140	140			
			Sc 2	5	5	5	5	5	5	5	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	135	135			
			Sc 3								5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	1	136	136			
			Sc 4											5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	125	125			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1								8	8	8	8	8	8	8	8														110	110			
			Sc 2	8	8		8	8	6	8	8	8	8	8	8	8	8	8														110	110			
			Sc 3																													46	46			

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
			Sc 4									8	8	8		8	8		8	8	8											110	110			
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
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			Sc 4																																	
		Part 15	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1												10	16	16	8														50	50			
			Sc 2												16	10	16	16														58	58			
			Sc 3											16	10																	26	26			
			Sc 4								16							10														26	26			
		Part 2	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 3	Sc 1																																	
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		Part 4	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1								8	8	8	8	8	8	8	8	8	8												136	136			
			Sc 2	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8												136	136			
			Sc 3								8	8	8	8	8	8	8	8	8	8												136	136			
			Sc 4								8	8	8	8	8	8	8	8	8	8												136	136			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1													16		6														76	76			
			Sc 2		16		16		6	16			16				12															82	82			
			Sc 3												12			14														80	80			
			Sc 4															4	16													74	74			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1								8	8	4																			50	50			
			Sc 2	8	6	8		8				8		4	8																	50	50			
			Sc 3											5																		35	35			
			Sc 4											5																		35	35			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1								5					5								3	5	5	5	5				33	33			
			Sc 2										5			5			5	5	5	5			5	5	5	5				50	50			
			Sc 3																					5	5	5	5	5				25	25			
			Sc 4																					5	5	5	5	5	5	5		35	35			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1															2														2	2			
			Sc 2																16	16	10											42	42			
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4												5	5																10	10			
		Part 3	Sc 1																																	
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		Part 4	Sc 1																																	
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			Sc 4																																	
		Part 5	Sc 1																																	
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Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	Due
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**produced**	**delivered**	**shops**	**qty**	**date**
			Sc 3																																	
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		Part 6	Sc 1																																	
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		Part 9	Sc 1																																	
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		Part 14	Sc 1																																	
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		Part 15	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
	Job 9	Part 1	Sc 1																																	
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			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																									8	8	8	24	24			
			Sc 2																									8	8	8	24	24			
			Sc 3																									8	8	8	24	24			
			Sc 4																									8	8	8	24	24			
		Part 4	Sc 1																																	
			Sc 2																				4	4	4	4	4	4	4		28	28			
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
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		Part 11	Sc 1																																	
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		Part 12	Sc 1																																	
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		Part 13	Sc 1																																	

Appendix 5: Production Schedule - All Scenarios

				Day in the planning horizon																												Sum produced	Sum delivered	Sum all shops	Demand qty	Due date
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**					
			Sc 2																																	
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		Part 14	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1								5	5	3																			48	48			
			Sc 2	5	5	5	5	5	5	5	5	5	3																			48	48			
			Sc 3								5	5	3																			48	48			
			Sc 4								5	5																				45	45			
	Job 1(	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3								16																					16	16			
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1										8	8	3																	19	19			
			Sc 2										8	8	3																	19	19			
			Sc 3										8	8	8	4																28	28			
			Sc 4										8	8	8	4																28	28			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
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		Part 6	Sc 1																																	
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		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1											5	4	5	5	5														24	24			
			Sc 2										2	5	5	2	5	5														24	24			
			Sc 3										2	5	5	5	5	2														24	24			
			Sc 4																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**Due date**
Shop 1	Job 1	Part 1	Sc 1																															150	150	24
			Sc 2																															150	150	27
			Sc 3																															150	150	21
			Sc 4																															150	150	21
		Part 2	Sc 1								1	5																				6	6	120	120	9
			Sc 2										1																			1	1	120	120	12
			Sc 3								1																					1	1	120	120	8
			Sc 4								6	5																				11	11	120	120	8
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1										6				8	8	8	8	8			8	8	2						64	64	120	120	14
			Sc 2											6						24	8		8		2							48	48	120	120	17
			Sc 3											38	8				8		8		8	8		2						80	80	120	120	11
			Sc 4											38	8		8				2	8			8	8						80	80	120	120	11
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 8	Sc 1																															130	130	19
			Sc 2																															130	130	19
			Sc 3																															130	130	19
			Sc 4																			24										24	24	130	130	19
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1										50																			50	50	50	50	10
			Sc 2										50																			50	50	50	50	10
			Sc 3										34																			34	34	50	50	10
			Sc 4										34																			34	34	50	50	10
		Part 11	Sc 1																															70	70	11
			Sc 2																															70	70	11
			Sc 3																															70	70	11
			Sc 4																															70	70	11
		Part 12	Sc 1								45																					45	45	45	45	8
			Sc 2								45																					45	45	45	45	8
			Sc 3								45																					45	45	45	45	8
			Sc 4								45																					45	45	45	45	8
		Part 13	Sc 1																															49	49	23
			Sc 2																															49	49	23
			Sc 3																															49	49	23
			Sc 4																															49	49	23
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																										16			16	16	30	30	26
			Sc 2																															30	30	26
			Sc 3																										20			20	20	30	30	26
			Sc 4																										20			20	20	30	30	26
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1															15													65	80	80	150	150	28
			Sc 2															25													65	90	90	150	150	28
			Sc 3															18													65	83	83	150	150	28
			Sc 4															10													65	75	75	150	150	28
		Part 3	Sc 1																	7	4	4	4	4	4	4	4					35	35	140	140	18
			Sc 2																		28	4	4	4								40	40	140	140	18
			Sc 3																		12	4	4	4	4	4	3					35	35	140	140	18
			Sc 4																	8	4	4	4	4	4	4	3					35	35	140	140	18
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1														29							3								32	32	120	120	21
			Sc 2															24														24	24	120	120	24
			Sc 3																		58											58	58	120	120	18
			Sc 4												29						29											58	58	120	120	18
		Part 6	Sc 1																															150	150	20
			Sc 2																															150	150	23
			Sc 3																															150	150	17
			Sc 4																															150	150	17
		Part 7	Sc 1																															120	120	14
			Sc 2																															120	120	17
			Sc 3																															120	120	11
			Sc 4																															120	120	11
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1								40																					40	40	80	80	8
			Sc 2								40																					40	40	80	80	8
			Sc 3								40																					40	40	80	80	8

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																								Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**					
			Sc 4								40																					40	40	80	80	8
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1														45	5	5	5		5	1									66	66	110	110	14
			Sc 2												35		10	5	5		5	5	5									70	70	110	110	14
			Sc 3														26	5	5		5	5	5									51	51	110	110	14
			Sc 4													25	5	5	5	5		1	5									51	51	110	110	14
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															120	120	17
			Sc 2																															120	120	17
			Sc 3																															120	120	17
			Sc 4																															120	120	17
		Part 14	Sc 1													21							21									60	60	180	180	20
			Sc 2													21							21									60	60	180	180	20
			Sc 3															27					15									60	60	180	180	20
			Sc 4				12		6									27					15									60	60	180	180	20
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1																															100	100	13
			Sc 2																															100	100	13
			Sc 3																															100	100	13
			Sc 4																															100	100	13
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1								32	4																				36	36	140	140	9
			Sc 2									36																				36	36	140	140	9
			Sc 3									36																				36	36	140	140	9
			Sc 4								32	4																				36	36	140	140	9
		Part 4	Sc 1									16				32																48	48	140	140	13
			Sc 2													48	8															56	56	140	140	13
			Sc 3													8	8	8														24	24	140	140	13
			Sc 4													8		8	8													24	24	140	140	13
		Part 5	Sc 1																															60	60	24
			Sc 2																															60	60	24
			Sc 3																															60	60	24
			Sc 4																															60	60	24
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															180	180	19
			Sc 2																															180	180	22
			Sc 3																															180	180	19
			Sc 4																															180	180	16
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1											96																		126	126	200	200	11
			Sc 2														112															142	142	200	200	14
			Sc 3								96																					126	126	200	200	8
			Sc 4	16	14						96																					126	126	200	200	8
		Part 11	Sc 1																															50	50	13
			Sc 2																															50	50	16
			Sc 3																															50	50	10
			Sc 4																															50	50	10
		Part 12	Sc 1																		116											116	116	150	150	18
			Sc 2								48										68											116	116	150	150	18
			Sc 3															75														75	75	150	150	15
			Sc 4																		116											116	116	150	150	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																					42								42	42	120	120	21
			Sc 2																					47								47	47	120	120	21
			Sc 3																							8	4					12	12	120	120	21
			Sc 4																							8	4					12	12	120	120	21
	Job 4	Part 1	Sc 1								20																					28	28	110	110	8
			Sc 2								20																					28	28	110	110	8
			Sc 3								26																					34	34	110	110	8
			Sc 4			8					26																					34	34	110	110	8
		Part 2	Sc 1																															50	50	24
			Sc 2																															50	50	24
			Sc 3																															50	50	24
			Sc 4																															50	50	24
		Part 3	Sc 1																																	
			Sc 2																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	delivered	produced	shops	qty	Due date
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																			8	8			6	8					30	30	30	30	17
			Sc 2																			8		8	6	8						30	30	30	30	17
			Sc 3																	8		8			8	6						30	30	30	30	17
			Sc 4																	8	6		8	8								30	30	30	30	17
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1												96																	96	96	100	100	12
			Sc 2												82																	82	82	100	100	12
			Sc 3												96																	96	96	100	100	12
			Sc 4											88	8																	96	96	100	100	12
		Part 9	Sc 1								16	8	8	8	8	8	8	8	8	8	8	8									3	115	115	120	120	8
			Sc 2								16	8	8	8	8	8	8	8	8	8	8	8										112	112	120	120	8
			Sc 3								16	8	8	8	8	8	8	8	8	8	8	8							7			119	119	120	120	8
			Sc 4			8					16	8	8	8	8	8	8		8	8	8	8									1	105	105	120	120	8
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 2																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 3																					5	5	5	5	5	5	5	5	40	40	66	80	21
			Sc 4																					5	5	5	5	5	5	5	5	40	40	66	80	21
		Part 12	Sc 1															50														50	50	50	50	15
			Sc 2																		50											50	50	50	50	18
			Sc 3															50														50	50	50	50	15
			Sc 4												50																	50	50	50	50	12
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																					3								3	3	80	80	21
			Sc 2																								12	3	3	3	3	24	24	80	80	24
			Sc 3																															80	80	18
			Sc 4																															80	80	18
		Part 15	Sc 1																								30					30	30	60	60	24
			Sc 2																											49		49	49	60	60	27
			Sc 3																					48	8							56	56	60	60	21
			Sc 4																					37	8							45	45	60	60	21
	Job 5	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1														12	4	1									4	4	4	4	33	33	122	150	14
			Sc 2																						4	4	4	4	4	4	4	28	28	122	150	17
			Sc 3											4	4	4	4	4									1	4	4	4	4	37	37	122	150	11
			Sc 4											4	4	4	4	4									1	4	4	4	4	37	37	122	150	11
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1												6																	6	6	110	110	12
			Sc 2												6																	6	6	110	110	15
			Sc 3									16																				16	16	110	110	9
			Sc 4								11	5																				16	16	110	110	8
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															40	40	17
			Sc 2																															40	40	20
			Sc 3																															40	40	14
			Sc 4																															40	40	14
		Part 9	Sc 1																															50	50	11
			Sc 2																															50	50	11
			Sc 3																															50	50	11
			Sc 4															8													2	10	10	50	50	11
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1											25							5		4									34	34	130	130	14
			Sc 2														25			5												30	30	130	130	14
			Sc 3													29				5												34	34	130	130	14
			Sc 4											25							5	4										34	34	130	130	14
		Part 12	Sc 1																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	delivered	produced	shops	qty	Due date
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															120	120	27
			Sc 2																															120	120	27
			Sc 3																															120	120	27
			Sc 4																															120	120	27
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																															20	20	8
			Sc 2																															20	20	11
			Sc 3																															20	20	8
			Sc 4																															20	20	8
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																															150	150	10
			Sc 2																															150	150	13
			Sc 3																															150	150	10
			Sc 4																															150	150	10
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																															140	140	11
			Sc 2																															140	140	11
			Sc 3																															140	140	8
			Sc 4																															140	140	14
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																															110	110	15
			Sc 2																															110	110	15
			Sc 3																															110	110	12
			Sc 4																															110	110	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1																															80	80	15
			Sc 2																															80	80	15
			Sc 3									8			22																	30	30	80	80	12
			Sc 4																															80	80	18
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																															140	140	17
			Sc 2																															140	140	17
			Sc 3																															140	140	17
			Sc 4																															140	140	17

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**Due date**
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1															24	8													32	32	150	150	16
			Sc 2																															150	150	19
			Sc 3																32													32	32	150	150	16
			Sc 4																32													32	32	150	150	16
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																															50	50	10
			Sc 2																															50	50	13
			Sc 3										15																			15	15	50	50	10
			Sc 4										15																			15	15	50	50	10
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																								9	3	3	3	3	21	21	70	70	24
			Sc 2																															70	70	24
			Sc 3																					3	3	3	3	3	3	3	3	24	24	70	70	21
			Sc 4																					3						18	3	24	24	70	70	27
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1															48														48	48	50	50	15
			Sc 2																		8											8	8	50	50	18
			Sc 3															34														34	34	50	50	15
			Sc 4														50															50	50	50	50	15
		Part 2	Sc 1								39		5	5	5																	54	54	70	70	10
			Sc 2										49																			49	49	70	70	10
			Sc 3								39	5	5	5	2																	56	56	70	70	8
			Sc 4													54																54	54	70	70	13
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																				30									30	30	30	30	20
			Sc 2																				30									30	30	30	30	20
			Sc 3																	30												30	30	30	30	17
			Sc 4																							30						30	30	30	30	23
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																						16	8	8	8				40	40	40	40	22
			Sc 2																						24	8	8					40	40	40	40	22
			Sc 3																						16	8	8	8				40	40	40	40	22
			Sc 4																						16	8	8	8				40	40	40	40	22
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1														70															70	70	70	70	14
			Sc 2																	70												70	70	70	70	17
			Sc 3														70															70	70	70	70	14
			Sc 4														70															70	70	70	70	14
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	delivered	produced	shops	qty	Due date
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 9	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																															24	150	15
			Sc 2																															24	150	18
			Sc 3																															24	150	15
			Sc 4																															24	150	15
		Part 4	Sc 1																															200	200	18
			Sc 2																															200	200	21
			Sc 3																															200	200	18
			Sc 4																															200	200	18
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																															70	70	20
			Sc 2																															70	70	20
			Sc 3																															70	70	20
			Sc 4																															70	70	20
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																															50	50	10
			Sc 2																															50	50	10
			Sc 3																															50	50	10
			Sc 4																															50	50	10
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																60													60	60	60	60	16
			Sc 2																60													60	60	60	60	16
			Sc 3													48																48	48	60	60	13
			Sc 4																			60										60	60	60	60	19
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																															80	80	12
			Sc 2																															80	80	12
			Sc 3																															80	80	9
			Sc 4																															80	80	15
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																															120	120	9
			Sc 2																															120	120	9
			Sc 3																															120	120	9
			Sc 4																															120	120	9
	Job 10	Part 1	Sc 1																															90	90	11
			Sc 2																															90	90	11
			Sc 3								2																					2	2	90	90	8
			Sc 4																															90	90	14
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1										4	4																		8	8	50	50	10
			Sc 2										4	4																		8	8	50	50	10
			Sc 3										4																			4	4	50	50	10
			Sc 4										4																			4	4	50	50	10
		Part 4	Sc 1								50																					50	50	100	100	8
			Sc 2								50																					50	50	100	100	8
			Sc 3								50																					50	50	100	100	8
			Sc 4								50																					50	50	100	100	8
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																								Sum	Sum	Sum all	Demand	
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**Due date**
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																				8						8	8	5	29	29	70	70	20
			Sc 2																									8	8	8	8	32	32	70	70	23
			Sc 3																				8						1	8	8	25	25	70	70	20
			Sc 4																				8						8	8	5	29	29	70	70	20
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																		7											7	7	60	60	18
			Sc 2																					55								55	55	60	60	21
			Sc 3																		48											48	48	60	60	18
			Sc 4																		7											7	7	60	60	18
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1													56		16														120	120	200	200	15
			Sc 2													56		16														120	120	200	200	15
			Sc 3								16				32	8	8	8														120	120	200	200	12
			Sc 4						48				19								64											131	131	200	200	18
Shop 2	Job 1	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																					8								8	8			
			Sc 4																																	
		Part 2	Sc 1									24																				64	64			
			Sc 2												23																	63	63			
			Sc 3								24	2																				66	66			
			Sc 4					40			24																					64	64			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																	44	4											48	48			
			Sc 3											16	16																	32	32			
			Sc 4											16	16																	32	32			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																			18	8									26	26			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																										5			5	5			
			Sc 3																																	
			Sc 4																																	
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																												70	70	70			

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 2																												60	60	60			
			Sc 3																												67	67	67			
			Sc 4																												75	75	75			
		Part 3	Sc 1																		10	5	5	5								25	25			
			Sc 2																		5	2										7	7			
			Sc 3																		10	5	5	5								25	25			
			Sc 4																		10	5	5	5								25	25			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																					60	8							68	68			
			Sc 2																								84	8				92	92			
			Sc 3																		46	8										54	54			
			Sc 4																		46	8										54	54			
		Part 6	Sc 1																	88			2									90	90			
			Sc 2															80								34						114	114			
			Sc 3											64						26												90	90			
			Sc 4																90													90	90			
		Part 7	Sc 1														120															120	120			
			Sc 2																	120												120	120			
			Sc 3											120																		120	120			
			Sc 4											120																		120	120			
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1								35																					40	40			
			Sc 2								35																					40	40			
			Sc 3								35																					40	40			
			Sc 4	5							35																					40	40			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																	120												120	120			
			Sc 2																	120												120	120			
			Sc 3																	120												120	120			
			Sc 4																	120												120	120			
		Part 14	Sc 1																				70									100	100			
			Sc 2																				70									100	100			
			Sc 3																				70									100	100			
			Sc 4		10				20														70									100	100			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3													8																8	8			
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1									32																				32	32			
			Sc 2									32																				32	32			
			Sc 3									32																				32	32			
			Sc 4								27	5																				32	32			
		Part 4	Sc 1													48	16	16														80	80			
			Sc 2													36	16	4														56	56			
			Sc 3													16	16	16	8													56	56			
			Sc 4													16	16	16	8													56	56			
		Part 5	Sc 1																								16					16	16			
			Sc 2																																	
			Sc 3																								4					4	4			
			Sc 4																								4					4	4			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																			16	8	8								32	32			
			Sc 2																						16	8						24	24			
			Sc 3																			24	8	8								40	40			
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum delivered**	**Sum produced**	**Sum all shops**	**Demand qty**	**Due date**
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3															1														1	1			
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																					40								40	40			
			Sc 2																					40								40	40			
			Sc 3																					36	8	8	8					60	60			
			Sc 4																					9	8	8	8					33	33			
	Job 4	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1												4																	4	4			
			Sc 2											2																		2	2			
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1									5																				5	5			
			Sc 2									5																				5	5			
			Sc 3									1																				1	1			
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																									4	4	4	4	16	16			
			Sc 2																										4	4	4	12	12			
			Sc 3																									4	4	4	4	16	16			
			Sc 4																									4	4	4	4	16	16			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																					5								5	5			
			Sc 2																									1				1	1			
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																								24					24	24			
			Sc 2																											6		6	6			
			Sc 3																					4								4	4			
			Sc 4																					15								15	15			
	Job 5	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1														15	5	5						5	5	5	5	5	5	5	60	60			
			Sc 2																	30		3	5	5	5	5	5	5	5	5	5	78	78			
			Sc 3											5	5	5	5	5	5						5	5	5	5	5	5	5	65	65			
			Sc 4											5	5	5	5	5	5						5	5	5	5	5	5	5	65	65			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**Due date**
			Sc 4																																	
		Part 5	Sc 1											40	8	8																104	104			
			Sc 2															56														104	104			
			Sc 3									24	8	8	6																	94	94			
			Sc 4						48		16	8	8	8	6																	94	94			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																	40												40	40			
			Sc 2																				40									40	40			
			Sc 3														40															40	40			
			Sc 4														40															40	40			
		Part 9	Sc 1											10	5	5	5	5	5	5	5	5										50	50			
			Sc 2											10		5	5	5	5	5	5	5	5									50	50			
			Sc 3											10	5	5	5	5	5	5	5	5										50	50			
			Sc 4									5		10	5	5				5	5	5										40	40			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1														52	4	4	4	4	4	4	4	4	4	4					96	96			
			Sc 2														52	4	4	4	4	4	4	4	4	4	4	4				100	100			
			Sc 3														52	4	4	4	4	4	4	4	4	4	4					96	96			
			Sc 4	4													52	4	4	4	4	4	4	4	4	4	4					96	96			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																											56		120	120			
			Sc 2																											56		120	120			
			Sc 3																											56		120	120			
			Sc 4							64																				56		120	120			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1								8																					8	8			
			Sc 2											11																		11	11			
			Sc 3											8																		8	8			
			Sc 4									8	2																			10	10			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1										110																			110	110			
			Sc 2													122																122	122			
			Sc 3										110																			110	110			
			Sc 4									94	16																			110	110			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
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		Part 7	Sc 1																																	
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		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2												5																	5	5			
			Sc 3									4																				4	4			
			Sc 4														5	5	5													15	15			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3												64																	64	64			
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**delivered**	**produced**	**shops**	**qty**	**Due date**
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1															30														30	30			
			Sc 2															22														22	22			
			Sc 3												24																	24	24			
			Sc 4																		54											54	54			
		Part 2	Sc 1																																	
			Sc 2																																	
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		Part 3	Sc 1																																	
			Sc 2																																	
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		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																	4												4	4			
			Sc 2														4															4	4			
			Sc 3																	4												4	4			
			Sc 4																	4												4	4			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1															42														42	42			
			Sc 2																			68										68	68			
			Sc 3																38													38	38			
			Sc 4											14					24	6												44	44			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
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		Part 12	Sc 1																																	
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			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																								15	1				16	16			
			Sc 2																								20					20	20			
			Sc 3																					5	5	5	5	1				21	21			
			Sc 4																											11		11	11			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3															16														16	16			
			Sc 4																																	
		Part 2	Sc 1										8	8																		16	16			
			Sc 2										21																			21	21			
			Sc 3									6	8																			14	14			
			Sc 4													6																6	6			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 5	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum delivered**	**Sum produced**	**Sum all shops**	**Demand qty**	**Due date**
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 9	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																		48	16	16	16	16	16	16	16	16	16	8	200	200			
			Sc 2																					60	16	16	16	16	16	16	16	172	172			
			Sc 3																		40	16	16	16	16	16	16	16	16	16	16	200	200			
			Sc 4																		40	16	16	16	16	16	16	16	16	16	16	200	200			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																				62									70	70			
			Sc 2																				62									70	70			
			Sc 3																				62									70	70			
			Sc 4							8													62									70	70			
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1										50																			50	50			
			Sc 2										50																			50	50			
			Sc 3										50																			50	50			
			Sc 4										50																			50	50			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3													12																12	12			
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1												80																	80	80			
			Sc 2												80																	80	80			
			Sc 3									80																				80	80			
			Sc 4															80														80	80			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1									24																				72	72			
			Sc 2									24																				72	72			
			Sc 3									24																				72	72			
			Sc 4						48			24	3																			75	75			

Appendix 6: Delivery Schedule - All Scenario

Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
	Job 10	Part 1	Sc 1											88	2																	90	90			
			Sc 2											88	2																	90	90			
			Sc 3								64	8																				72	72			
			Sc 4														90															90	90			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1									13	5	5																		23	23			
			Sc 2									13	5	5																		23	23			
			Sc 3								13		5																			18	18			
			Sc 4										18																			18	18			
		Part 4	Sc 1								34																					50	50			
			Sc 2								34																					50	50			
			Sc 3								34																					50	50			
			Sc 4	16							34																					50	50			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																				5	5	5	5	5	5	5	5	1	41	41			
			Sc 2																							15	5	5	5	5	3	38	38			
			Sc 3																				5	5	5	5	5	5	5	5	5	45	45			
			Sc 4																				5	5	5	5	5	5	5	5	1	41	41			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1																		53											53	53			
			Sc 2																					5								5	5			
			Sc 3																		12											12	12			
			Sc 4																		53											53	53			
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1													32		16	8													56	56			
			Sc 2													32		16	8													56	56			
			Sc 3												24	8	8	8	8													56	56			
			Sc 4																		69											69	69			
Shop 3	Job 1	Part 1	Sc 1																								150					150	150			
			Sc 2																											150		150	150			
			Sc 3																					12	16							142	142			
			Sc 4																					13	16							150	150			
		Part 2	Sc 1									10	5	5																		50	50			
			Sc 2												21	5																56	56			
			Sc 3								10	5	5	3																		53	53			
			Sc 4	5					25		10	5																				45	45			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1														4	4	4	4	4	4	4	4	4	4	4	4	4	4		56	56			
			Sc 2																	12	4	4	4									24	24			
			Sc 3											4	4																	8	8			
			Sc 4											4	4																	8	8			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																				54									70	70			
			Sc 2																				54									70	70			
			Sc 3																				54									70	70			
			Sc 4				16																54									70	70			
		Part 8	Sc 1																			130										130	130			
			Sc 2								16											114										130	130			
			Sc 3																			130										130	130			
			Sc 4																			48	16	16								80	80			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum	Sum	Sum all	Demand	
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	delivered	produced	shops	qty	Due date
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3										16																			16	16			
			Sc 4										16																			16	16			
		Part 11	Sc 1											4								4	8	8	8		8	6	8	8	8	70	70			
			Sc 2											20										8		8	8	2	8	8	8	70	70			
			Sc 3											3								5	8	8	6	8	8		8	8	8	70	70			
			Sc 4											3								5	8	8	8	8		8	6	8	8	70	70			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																							49						49	49			
			Sc 2																							49						49	49			
			Sc 3																							49						49	49			
			Sc 4																							49						49	49			
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																										14			14	14			
			Sc 2																										25			25	25			
			Sc 3																										10			10	10			
			Sc 4																										10			10	10			
	Job 2	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																		24	8	8	8	8	8	8	8				80	80			
			Sc 2																		53	8	8	8	8	8						93	93			
			Sc 3																		24	8	8	8	8	8	8	8				80	80			
			Sc 4																		24	8	8	8	8	8	8	8				80	80			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																					20								20	20			
			Sc 2																								4					4	4			
			Sc 3																		8											8	8			
			Sc 4																		8											8	8			
		Part 6	Sc 1																				60									60	60			
			Sc 2																							36						36	36			
			Sc 3																	60												60	60			
			Sc 4																	60												60	60			
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1														8	8	8	8	8	4										44	44			
			Sc 2														16				8	8	8									40	40			
			Sc 3														24	8	8	8	8	3										59	59			
			Sc 4														24	8	8	8	8	3										59	59			
		Part 12	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																				20									20	20			
			Sc 2																	15			5									20	20			
			Sc 3																				20									20	20			
			Sc 4									5											15									20	20			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 3	Part 1	Sc 1													100																100	100			
			Sc 2													100																100	100			
			Sc 3													90	2															92	92			
			Sc 4													100																100	100			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1									72																				72	72			
			Sc 2									72																				72	72			

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																																
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
			Sc 3								64	8																				72	72			
			Sc 4								64	8																				72	72			
		Part 4	Sc 1													12																12	12			
			Sc 2								4					20	4															28	28			
			Sc 3													4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		60	60			
			Sc 4													4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		60	60			
		Part 5	Sc 1																								36	8				44	44			
			Sc 2																								52	8				60	60			
			Sc 3																								48	8				56	56			
			Sc 4																								48	8				56	56			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																			82	16	16	16	2						148	148			
			Sc 2																						108	16	16					156	156			
			Sc 3																			74	16	16	16	2						140	140			
			Sc 4		16														162						2							180	180			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1											42																		74	74			
			Sc 2														26															58	58			
			Sc 3								42																					74	74			
			Sc 4					32			42																					74	74			
		Part 11	Sc 1													50																50	50			
			Sc 2									26							16	8												50	50			
			Sc 3										50																			50	50			
			Sc 4										50																			50	50			
		Part 12	Sc 1																		26											34	34			
			Sc 2																		26											34	34			
			Sc 3															66														74	74			
			Sc 4				8														26											34	34			
		Part 13	Sc 1																																	
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		Part 14	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1															3						30	5							38	38			
			Sc 2																			23		10								33	33			
			Sc 3																					33	5	5	5					48	48			
			Sc 4															30						30	5	5	5					75	75			
	Job 4	Part 1	Sc 1								54																					82	82			
			Sc 2								54																					82	82			
			Sc 3								48																					76	76			
			Sc 4			28					48																					76	76			
		Part 2	Sc 1																								50					50	50			
			Sc 2																								50					50	50			
			Sc 3																								50					50	50			
			Sc 4																								50					50	50			
		Part 3	Sc 1																																	
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		Part 5	Sc 1																																	
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			Sc 4																																	
		Part 6	Sc 1																				70									70	70			
			Sc 2																				70									70	70			
			Sc 3																				70									70	70			
			Sc 4																				70									70	70			
		Part 7	Sc 1																																	
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		Part 8	Sc 1																																	
			Sc 2												16																	16	16			
			Sc 3												4																	4	4			
			Sc 4												4																	4	4			
		Part 9	Sc 1																																	
			Sc 2								3																					3	3			
			Sc 3																																	
			Sc 4								5	5	5																			15	15			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																							8		2				10	10			
			Sc 2																						8			6				14	14			
			Sc 3																						2			8				10	10			
			Sc 4																								8		2			10	10			
		Part 12	Sc 1																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	
Shop	Job	Part	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					Due date
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1															45						12								72	72			
			Sc 2												25												15					55	55			
			Sc 3																		65											80	80			
			Sc 4			15						25									40											80	80			
		Part 15	Sc 1																								6					6	6			
			Sc 2																											5		5	5			
			Sc 3																																	
			Sc 4																																	
	Job 5	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1														21	8														29	29			
			Sc 2																								8	8				16	16			
			Sc 3													4	8	8														20	20			
			Sc 4													4	8	8														20	20			
		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
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			Sc 4																																	
		Part 6	Sc 1																																	
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			Sc 4																																	
		Part 7	Sc 1																																	
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		Part 8	Sc 1																																	
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		Part 10	Sc 1																																	
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		Part 11	Sc 1																																	
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		Part 12	Sc 1																																	
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		Part 13	Sc 1																																	
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			Sc 4																																	
		Part 14	Sc 1																																	
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			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 6	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1								5				5	2																12	12			
			Sc 2											9																		9	9			
			Sc 3											2	5	5																12	12			
			Sc 4										5	5																		10	10			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1										24																			40	40			
			Sc 2										12																			28	28			
			Sc 3										24																			40	40			
			Sc 4				16						24																			40	40			
		Part 5	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	

Appendix 6: Delivery Schedule - All Scenario

				Day in the planning horizon																																
Shop	**Job**	**Part**	**Scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**Sum delivered**	**Sum produced**	**Sum all shops**	**Demand qty**	**Due date**
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1									45	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	140	140			
			Sc 2											52	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	135	135			
			Sc 3								40	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	1	136	136			
			Sc 4														55	5	5	5	5	5	5	5	5	5	5	5	5	5	5	125	125			
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 12	Sc 1															94														110	110			
			Sc 2												70			24														110	110			
			Sc 3												30																	46	46			
			Sc 4			16															94											110	110			
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 7	Part 1	Sc 1															50														50	50			
			Sc 2															58														58	58			
			Sc 3												26																	26	26			
			Sc 4																		26											26	26			
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
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		Part 3	Sc 1																																	
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		Part 4	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1												48					40												136	136			
			Sc 2															72		16												136	136			
			Sc 3													56				32												136	136			
			Sc 4						48					40						48												136	136			
		Part 6	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 7	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 8	Sc 1																76													76	76			
			Sc 2																			82										82	82			
			Sc 3																80													80	80			
			Sc 4																74													74	74			
		Part 9	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 10	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 11	Sc 1										28																			50	50			
			Sc 2													28																50	50			
			Sc 3										8	5																		35	35			
			Sc 4			22							8	5																		35	35			
		Part 12	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 13	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 14	Sc 1																								28	5				33	33			
			Sc 2																								45	5				50	50			
			Sc 3																					5	5	5	5	5				25	25			

Appendix 6: Delivery Schedule - All Scenario

Shop	Job	Part	Scenario	Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 4																											35		35	35			
		Part 15	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
	Job 8	Part 1	Sc 1															2														2	2			
			Sc 2																		42											42	42			
			Sc 3																																	
			Sc 4																																	
		Part 2	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4												5	5																10	10			
		Part 3	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 4	Sc 1																																	
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		Part 5	Sc 1																																	
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		Part 6	Sc 1																																	
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		Part 7	Sc 1																																	
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		Part 8	Sc 1																																	
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		Part 9	Sc 1																																	
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		Part 10	Sc 1																																	
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		Part 11	Sc 1																																	
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		Part 15	Sc 1																																	
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	Job 9	Part 1	Sc 1																																	
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			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 3	Sc 1																									8	8	8	24	24			
			Sc 2																									8	8	8	24	24			
			Sc 3																									8	8	8	24	24			
			Sc 4																									8	8	8	24	24			
		Part 4	Sc 1																																	
			Sc 2																				4	4	4	4	4	4	4		28	28			
			Sc 3																																	
			Sc 4																																	
		Part 5	Sc 1																																	
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		Part 6	Sc 1																																	
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		Part 7	Sc 1																																	
			Sc 2																																	
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			Sc 4																																	
		Part 8	Sc 1																																	
			Sc 2																																	

Appendix 6: Delivery Schedule - All Scenario

Shop	Job	Part	Scenario	Day in the planning horizon																												Sum delivered	Sum produced	Sum all shops	Demand qty	Due date
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28					
			Sc 3																																	
			Sc 4																																	
		Part 9	Sc 1																																	
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		Part 10	Sc 1																																	
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		Part 11	Sc 1																																	
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		Part 12	Sc 1																																	
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		Part 13	Sc 1																																	
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		Part 14	Sc 1																																	
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			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1								20	5	3																			48	48			
			Sc 2									25	3																			48	48			
			Sc 3								20	5	3																			48	48			
			Sc 4				20				20	5																				45	45			
	Job 10	Part 1	Sc 1																																	
			Sc 2																																	
			Sc 3								16																					16	16			
			Sc 4																																	
		Part 2	Sc 1																																	
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			Sc 4																																	
		Part 3	Sc 1										8	8	3																	19	19			
			Sc 2										8	8	3																	19	19			
			Sc 3										8	8	8	4																28	28			
			Sc 4										8	8	8	4																28	28			
		Part 4	Sc 1																																	
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		Part 5	Sc 1																																	
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		Part 6	Sc 1																																	
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		Part 10	Sc 1																																	
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		Part 13	Sc 1																																	
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			Sc 4																																	
		Part 14	Sc 1																																	
			Sc 2																																	
			Sc 3																																	
			Sc 4																																	
		Part 15	Sc 1												9			15														24	24			
			Sc 2													14		10														24	24			
			Sc 3												12	5	5	2														24	24			
			Sc 4																																	

Appendix 7. CPLEX Code for the Deterministic Model

MODEL FILE

```
/*********************************************
 * OPL 12.7.0.0 Model
 * Author: chung
 * Creation Date: Feb 22, 2017 at 3:58:36 AM
 *********************************************/

// execute gapTermination {
//    cplex.epgap < 0.03; // result at gap of 3%
//   }

// execute timeTermination {
//    cplex.tilim = 180; // maximum Runtime = 5 mins
//   }


// parameter
 int N=...;  //number of shop
 int M=...;  //number of job
 int K=...;  //number of job parts required for each job
 int L=...;  //number of all types of job parts
 int T=...;  //number of day in timeline
// int D=...;  //number of part with due date

 range shopID=1..N;
 range jobID=1..M;
 range partnameID=1..L;
 range jobpartID=1..K;
 range timelineID=1..T;

 string shopname[shopID]=...;
 string jobname[jobID]=...;
 string partname[partnameID]=...;

 float transcost[partnameID]=...;
 float pro_time[partnameID][shopID]=...;
 float pro_cost[partnameID][shopID]=...;
 float pro_cost_max[partnameID]=...;

 string jobpart[jobpartID][jobID]=...;
 float demand[jobpartID][jobID]=...;
 float duedate[jobpartID][jobID]=...;
 float delaycost[jobpartID][jobID]=...;
 float transdis[jobID][shopID]=...;
 float transdis_max[jobID]=...;
 int timeline[timelineID]=...;

 float jobpart_cost[jobpartID][jobID][shopID];
 float jobpart_cost_max[jobpartID][jobID];
 float jobpart_ptime[jobpartID][jobID][shopID];
 float jobpart_trcost[jobpartID][jobID];
```

```
 // variables
 dvar int+ jobpro[shopID][jobID][jobpartID][timelineID];
 dvar int+ jobpart_trans[shopID][jobID][jobpartID][timelineID];
 dvar int+ jobpart_tardy[jobpartID][jobID][timelineID];

 execute {
      //assign cost and processing time for jobpart:
      for (var j in jobID) {
             for (var k in jobpartID) {
                   for (var l in partnameID) {
                         for (var i in shopID) {
                                if (jobpart[k][j]==partname[l]) {
                                      jobpart_cost[k][j][i]=pro_cost[l][i];
                                      jobpart_ptime[k][j][i]=pro_time[l][i];
                                      jobpart_trcost[k][j]=transcost[l];
                                      jobpart_cost_max[k][j]=pro_cost_max[l];
                                      //writeln
("jobpart[",k,"][",j,"]=",jobpart[k][j]," has name as partname[",l,"]=",partname[l])
                                      //writeln
("pro_cost[",l,"][",i,"]=",pro_cost[l][i]);
                                      //writeln
("jobpart_cost[",k,"][",j,"][",i,"]=",jobpart_cost[k][j][i]);
                                      //writeln
("jobpart_ptime[",k,"][",j,"][",i,"]=",jobpart_ptime[k][j][i]);
                                }
                                else
                                      writeln ("No partname meet jobpart");

                         }
                   }
             }
      }
}

 dexpr float total_cost = sum(t in timelineID, k in jobpartID, j in jobID, i in
shopID) ( jobpart_cost[k][j][i] * jobpro[i][j][k][t])
 + sum(t in timelineID, k in jobpartID, j in jobID, i in shopID)
(jobpart_trcost[k][j] * jobpart_trans[i][j][k][t] * transdis[j][i])
 + sum(k in jobpartID, j in jobID, t in timelineID) (delaycost[k][j] *
jobpart_tardy[k][j][t])
 + sum(k in jobpartID, j in jobID) (jobpart_cost_max[k][j] * jobpart_tardy[k][j][28])
 + sum(k in jobpartID, j in jobID) (jobpart_trcost[k][j] * jobpart_tardy[k][j][28] *
transdis_max[j]);

// test result
dexpr float TTproc_cost = sum(t in timelineID, k in jobpartID, j in jobID, i in
shopID) ( jobpart_cost[k][j][i] * jobpro[i][j][k][t]);
dexpr float TTtrans_cost = sum(t in timelineID, k in jobpartID, j in jobID, i in
shopID) (jobpart_trcost[k][j] * jobpart_trans[i][j][k][t] * transdis[j][i]);
dexpr float TTtardy_cost = sum(k in jobpartID, j in jobID, t in timelineID)
(delaycost[k][j] * jobpart_tardy[k][j][t]);
dexpr float TTunmatch_proc = sum(k in jobpartID, j in jobID) (jobpart_cost_max[k][j]
* jobpart_tardy[k][j][28]);
```

```
dexpr float TTunmatch_transp = sum(k in jobpartID, j in jobID) (jobpart_trcost[k][j]
* jobpart_tardy[k][j][28] * transdis_max[j]);

dexpr float total_cost_v = sum(t in 1..7, k in jobpartID, j in jobID, i in shopID) (
jobpart_cost[k][j][i] * jobpro[i][j][k][t])
 + sum(t in 1..7, k in jobpartID, j in jobID, i in shopID) (jobpart_trcost[k][j] *
jobpro[i][j][k][t] * transdis[j][i])
 + sum(k in jobpartID, j in jobID, t in 1..7) (delaycost[k][j] *
jobpart_tardy[k][j][t]);

 // objectives
minimize total_cost;

 // constraints
 subject to
 {
      constraint_in_machine_availability:
             forall (i in shopID)
               forall (t in timelineID){
               jobpart_ptime[1][1][i] *jobpro[i][1][1][t]+jobpart_ptime[1][3][i]
*jobpro[i][3][1][t] <= 16;
               jobpart_ptime[2][1][i] *jobpro[i][1][2][t]+jobpart_ptime[1][2][i]
*jobpro[i][2][1][t] <= 16;
               jobpart_ptime[3][1][i] *jobpro[i][1][3][t]+jobpart_ptime[3][3][i]
*jobpro[i][3][3][t] <= 16;
               jobpart_ptime[4][1][i] *jobpro[i][1][4][t]+jobpart_ptime[5][2][i]
*jobpro[i][2][5][t] <= 16;
               jobpart_ptime[5][1][i] *jobpro[i][1][5][t]+jobpart_ptime[5][3][i]
*jobpro[i][3][5][t] <= 16;
               jobpart_ptime[2][2][i] *jobpro[i][2][2][t]+jobpart_ptime[2][3][i]
*jobpro[i][3][2][t] <= 16;
               jobpart_ptime[3][2][i] *jobpro[i][2][3][t]+jobpart_ptime[4][3][i]
*jobpro[i][3][4][t] <= 16;
               jobpart_ptime[4][2][i] *jobpro[i][2][4][t] <= 16;
               }


      constraint_in_tardy_job_1:
             forall (j in jobID, k in jobpartID, t in timelineID)
               if (t<duedate[k][j])
                    jobpart_tardy[k][j][t]==0;
      constraint_tardy_job_2:
             forall (j in jobID)
               forall (k in jobpartID)
                 forall (t in timelineID: t>=duedate[k][j])
                    sum(i in shopID, h in timelineID: h<=t) jobpart_trans[i][j][k][h]
+ jobpart_tardy[k][j][t] == demand[k][j];
      constraint_in_transportation_1:
             forall (j in jobID)
               forall (k in jobpartID)
                    sum(t in timelineID, i in shopID) jobpart_trans[i][j][k][t] ==
sum(t in timelineID, i in shopID) jobpro[i][j][k][t];
      constraint_in_transportation_2:
             forall (t in timelineID)
               forall (j in jobID)
```

```
                 forall (k in jobpartID)
                   forall (i in shopID)
                       sum(t_1 in 1..t) jobpart_trans[i][j][k][t_1] <= sum(t_1 in
1..t) jobpro[i][j][k][t_1];



 tuple someTuple1
  {
 int a;
 int b;
 int c;
 int d;
 int value;
  };

  {someTuple1} someSet1 = {<i,j,k,t, jobpro[i][j][k][t]> | t in timelineID, k in
jobpartID, j in jobID, i in shopID};
  {someTuple1} someSet2 = {<i,j,k,t, jobpart_trans[i][j][k][t]> | t in timelineID, k
in jobpartID, j in jobID, i in shopID};

 tuple someTuple2
  {
 int a;
 int value;
  };

  {someTuple2} someSet_1 = {<t, jobpro[1][1][1][t]> | t in timelineID};
  {someTuple2} someSet_2 = {<t, jobpro[1][1][2][t]> | t in timelineID};
  {someTuple2} someSet_3 = {<t, jobpro[1][1][3][t]> | t in timelineID};
  {someTuple2} someSet_4 = {<t, jobpro[1][1][4][t]> | t in timelineID};
  {someTuple2} someSet_5 = {<t, jobpro[1][1][5][t]> | t in timelineID};
  {someTuple2} someSet_6 = {<t, jobpro[1][2][1][t]> | t in timelineID};
  {someTuple2} someSet_7 = {<t, jobpro[1][2][2][t]> | t in timelineID};
  {someTuple2} someSet_8 = {<t, jobpro[1][2][3][t]> | t in timelineID};
  {someTuple2} someSet_9 = {<t, jobpro[1][2][4][t]> | t in timelineID};
  {someTuple2} someSet_10 = {<t, jobpro[1][2][5][t]> | t in timelineID};
  {someTuple2} someSet_11 = {<t, jobpro[1][3][1][t]> | t in timelineID};
  {someTuple2} someSet_12 = {<t, jobpro[1][3][2][t]> | t in timelineID};
  {someTuple2} someSet_13 = {<t, jobpro[1][3][3][t]> | t in timelineID};
  {someTuple2} someSet_14 = {<t, jobpro[1][3][4][t]> | t in timelineID};
  {someTuple2} someSet_15 = {<t, jobpro[1][3][5][t]> | t in timelineID};
  {someTuple2} someSet_16 = {<t, jobpro[2][1][1][t]> | t in timelineID};
  {someTuple2} someSet_17 = {<t, jobpro[2][1][2][t]> | t in timelineID};
  {someTuple2} someSet_18 = {<t, jobpro[2][1][3][t]> | t in timelineID};
  {someTuple2} someSet_19 = {<t, jobpro[2][1][4][t]> | t in timelineID};
  {someTuple2} someSet_20 = {<t, jobpro[2][1][5][t]> | t in timelineID};
  {someTuple2} someSet_21 = {<t, jobpro[2][2][1][t]> | t in timelineID};
  {someTuple2} someSet_22 = {<t, jobpro[2][2][2][t]> | t in timelineID};
  {someTuple2} someSet_23 = {<t, jobpro[2][2][3][t]> | t in timelineID};
  {someTuple2} someSet_24 = {<t, jobpro[2][2][4][t]> | t in timelineID};
  {someTuple2} someSet_25 = {<t, jobpro[2][2][5][t]> | t in timelineID};
  {someTuple2} someSet_26 = {<t, jobpro[2][3][1][t]> | t in timelineID};
  {someTuple2} someSet_27 = {<t, jobpro[2][3][2][t]> | t in timelineID};
  {someTuple2} someSet_28 = {<t, jobpro[2][3][3][t]> | t in timelineID};
```

```
 {someTuple2} someSet_29 = {<t, jobpro[2][3][4][t]> | t in timelineID};
 {someTuple2} someSet_30 = {<t, jobpro[2][3][5][t]> | t in timelineID};


 {someTuple2} someSet_T_1 = {<t, jobpart_trans[1][1][1][t]> | t in timelineID};
 {someTuple2} someSet_T_2 = {<t, jobpart_trans[1][1][2][t]> | t in timelineID};
 {someTuple2} someSet_T_3 = {<t, jobpart_trans[1][1][3][t]> | t in timelineID};
 {someTuple2} someSet_T_4 = {<t, jobpart_trans[1][1][4][t]> | t in timelineID};
 {someTuple2} someSet_T_5 = {<t, jobpart_trans[1][1][5][t]> | t in timelineID};
 {someTuple2} someSet_T_6 = {<t, jobpart_trans[1][2][1][t]> | t in timelineID};
 {someTuple2} someSet_T_7 = {<t, jobpart_trans[1][2][2][t]> | t in timelineID};
 {someTuple2} someSet_T_8 = {<t, jobpart_trans[1][2][3][t]> | t in timelineID};
 {someTuple2} someSet_T_9 = {<t, jobpart_trans[1][2][4][t]> | t in timelineID};
 {someTuple2} someSet_T_10 = {<t, jobpart_trans[1][2][5][t]> | t in timelineID};
 {someTuple2} someSet_T_11 = {<t, jobpart_trans[1][3][1][t]> | t in timelineID};
 {someTuple2} someSet_T_12 = {<t, jobpart_trans[1][3][2][t]> | t in timelineID};
 {someTuple2} someSet_T_13 = {<t, jobpart_trans[1][3][3][t]> | t in timelineID};
 {someTuple2} someSet_T_14 = {<t, jobpart_trans[1][3][4][t]> | t in timelineID};
 {someTuple2} someSet_T_15 = {<t, jobpart_trans[1][3][5][t]> | t in timelineID};
 {someTuple2} someSet_T_16 = {<t, jobpart_trans[2][1][1][t]> | t in timelineID};
 {someTuple2} someSet_T_17 = {<t, jobpart_trans[2][1][2][t]> | t in timelineID};
 {someTuple2} someSet_T_18 = {<t, jobpart_trans[2][1][3][t]> | t in timelineID};
 {someTuple2} someSet_T_19 = {<t, jobpart_trans[2][1][4][t]> | t in timelineID};
 {someTuple2} someSet_T_20 = {<t, jobpart_trans[2][1][5][t]> | t in timelineID};
 {someTuple2} someSet_T_21 = {<t, jobpart_trans[2][2][1][t]> | t in timelineID};
 {someTuple2} someSet_T_22 = {<t, jobpart_trans[2][2][2][t]> | t in timelineID};
 {someTuple2} someSet_T_23 = {<t, jobpart_trans[2][2][3][t]> | t in timelineID};
 {someTuple2} someSet_T_24 = {<t, jobpart_trans[2][2][4][t]> | t in timelineID};
 {someTuple2} someSet_T_25 = {<t, jobpart_trans[2][2][5][t]> | t in timelineID};
 {someTuple2} someSet_T_26 = {<t, jobpart_trans[2][3][1][t]> | t in timelineID};
 {someTuple2} someSet_T_27 = {<t, jobpart_trans[2][3][2][t]> | t in timelineID};
 {someTuple2} someSet_T_28 = {<t, jobpart_trans[2][3][3][t]> | t in timelineID};
 {someTuple2} someSet_T_29 = {<t, jobpart_trans[2][3][4][t]> | t in timelineID};
 {someTuple2} someSet_T_30 = {<t, jobpart_trans[2][3][5][t]> | t in timelineID};

tuple someTuple3
 {
 int a;
 int value;
 };

 {someTuple3} someSet_D_1 = {<t, jobpart_tardy[1][1][t]> | t in timelineID};
 {someTuple3} someSet_D_2 = {<t, jobpart_tardy[2][1][t]> | t in timelineID};
 {someTuple3} someSet_D_3 = {<t, jobpart_tardy[3][1][t]> | t in timelineID};
 {someTuple3} someSet_D_4 = {<t, jobpart_tardy[4][1][t]> | t in timelineID};
 {someTuple3} someSet_D_5 = {<t, jobpart_tardy[5][1][t]> | t in timelineID};
 {someTuple3} someSet_D_6 = {<t, jobpart_tardy[1][2][t]> | t in timelineID};
 {someTuple3} someSet_D_7 = {<t, jobpart_tardy[2][2][t]> | t in timelineID};
 {someTuple3} someSet_D_8 = {<t, jobpart_tardy[3][2][t]> | t in timelineID};
 {someTuple3} someSet_D_9 = {<t, jobpart_tardy[4][2][t]> | t in timelineID};
 {someTuple3} someSet_D_10 = {<t, jobpart_tardy[5][2][t]> | t in timelineID};
 {someTuple3} someSet_D_11 = {<t, jobpart_tardy[1][3][t]> | t in timelineID};
 {someTuple3} someSet_D_12 = {<t, jobpart_tardy[2][3][t]> | t in timelineID};
 {someTuple3} someSet_D_13 = {<t, jobpart_tardy[3][3][t]> | t in timelineID};
 {someTuple3} someSet_D_14 = {<t, jobpart_tardy[4][3][t]> | t in timelineID};
```

```
  {someTuple3} someSet_D_15 = {<t, jobpart_tardy[5][3][t]> | t in timelineID};

tuple someTuple4
  {
 int a;
 int value1;
 int value2;
 int value3;
  };
  {someTuple4} someSet_E_1 = {<k, sum(t in 1..7, i in shopID) ( jobpro[i][1][k][t]),
sum(t in 1..7, i in shopID) ( jobpro[i][2][k][t]), sum(t in 1..7, i in shopID) (
jobpro[i][3][k][t])> | k in jobpartID};
```

DATA FILE

```
/*********************************************
 * OPL 12.7.0.0 Data
 * Author: chung
 * Creation Date: Feb 22, 2017 at 3:58:36 AM
 *********************************************/
N=2;
M=3;
K=5;
L=15;
T=28;

SheetConnection my_sheet("Research_R03.xlsx");
SheetConnection my_sheet1("Graph_R03.xlsx");


//Shop data
shopname from SheetRead(my_sheet,"shopname");
jobname from SheetRead(my_sheet,"jobname");
partname from SheetRead(my_sheet,"partname");
transcost from SheetRead(my_sheet,"transcost");
pro_time from SheetRead(my_sheet,"pro_time");
pro_cost from SheetRead(my_sheet,"pro_cost");
pro_cost_max from SheetRead(my_sheet,"pro_cost_max");


//Job data
jobpart from SheetRead(my_sheet,"jobpart");
demand from SheetRead(my_sheet,"demand");
duedate from SheetRead(my_sheet,"duedate");
delaycost from SheetRead(my_sheet,"delaycost");
transdis from SheetRead(my_sheet,"transdis");
transdis_max from SheetRead(my_sheet,"transdis_max");


//Timeline
timeline from SheetRead(my_sheet,"timeline");
```

```
//Export result
total_cost to SheetWrite(my_sheet,"TotalCost"); //Total cost of the considered period
total_cost_v to SheetWrite(my_sheet,"TotalCost_v"); //Total cost at the first week of
the considered period

TTproc_cost to SheetWrite(my_sheet1,"BM36");
TTtrans_cost to SheetWrite(my_sheet1,"BM73");
TTtardy_cost to SheetWrite(my_sheet1,"BM110");
TTunmatch_proc to SheetWrite(my_sheet1,"BM114");
TTunmatch_transp to SheetWrite(my_sheet1,"BM117");

someSet1 to SheetWrite(my_sheet,"AG3:AK842");
someSet2 to SheetWrite(my_sheet,"BE3:BI842");

someSet_1 to SheetWrite(my_sheet1,"C8:D35");
someSet_2 to SheetWrite(my_sheet1,"E8:F35");
someSet_3 to SheetWrite(my_sheet1,"G8:H35");
someSet_4 to SheetWrite(my_sheet1,"I8:J35");
someSet_5 to SheetWrite(my_sheet1,"K8:L35");
someSet_6 to SheetWrite(my_sheet1,"M8:N35");
someSet_7 to SheetWrite(my_sheet1,"O8:P35");
someSet_8 to SheetWrite(my_sheet1,"Q8:R35");
someSet_9 to SheetWrite(my_sheet1,"S8:T35");
someSet_10 to SheetWrite(my_sheet1,"U8:V35");
someSet_11 to SheetWrite(my_sheet1,"W8:X35");
someSet_12 to SheetWrite(my_sheet1,"Y8:Z35");
someSet_13 to SheetWrite(my_sheet1,"AA8:AB35");
someSet_14 to SheetWrite(my_sheet1,"AC8:AD35");
someSet_15 to SheetWrite(my_sheet1,"AE8:AF35");
someSet_16 to SheetWrite(my_sheet1,"AG8:AH35");
someSet_17 to SheetWrite(my_sheet1,"AI8:AJ35");
someSet_18 to SheetWrite(my_sheet1,"AK8:AL35");
someSet_19 to SheetWrite(my_sheet1,"AM8:AN35");
someSet_20 to SheetWrite(my_sheet1,"AO8:AP35");
someSet_21 to SheetWrite(my_sheet1,"AQ8:AR35");
someSet_22 to SheetWrite(my_sheet1,"AS8:AT35");
someSet_23 to SheetWrite(my_sheet1,"AU8:AV35");
someSet_24 to SheetWrite(my_sheet1,"AW8:AX35");
someSet_25 to SheetWrite(my_sheet1,"AY8:AZ35");
someSet_26 to SheetWrite(my_sheet1,"BA8:BB35");
someSet_27 to SheetWrite(my_sheet1,"BC8:BD35");
someSet_28 to SheetWrite(my_sheet1,"BE8:BF35");
someSet_29 to SheetWrite(my_sheet1,"BG8:BH35");
someSet_30 to SheetWrite(my_sheet1,"BI8:BJ35");

someSet_T_1 to SheetWrite(my_sheet1,"C45:D72");
someSet_T_2 to SheetWrite(my_sheet1,"E45:F72");
someSet_T_3 to SheetWrite(my_sheet1,"G45:H72");
someSet_T_4 to SheetWrite(my_sheet1,"I45:J72");
someSet_T_5 to SheetWrite(my_sheet1,"K45:L72");
someSet_T_6 to SheetWrite(my_sheet1,"M45:N72");
someSet_T_7 to SheetWrite(my_sheet1,"O45:P72");
someSet_T_8 to SheetWrite(my_sheet1,"Q45:R72");
someSet_T_9 to SheetWrite(my_sheet1,"S45:T72");
someSet_T_10 to SheetWrite(my_sheet1,"U45:V72");
```

```
someSet_T_11 to SheetWrite(my_sheet1,"W45:X72");
someSet_T_12 to SheetWrite(my_sheet1,"Y45:Z72");
someSet_T_13 to SheetWrite(my_sheet1,"AA45:AB72");
someSet_T_14 to SheetWrite(my_sheet1,"AC45:AD72");
someSet_T_15 to SheetWrite(my_sheet1,"AE45:AF72");
someSet_T_16 to SheetWrite(my_sheet1,"AG45:AH72");
someSet_T_17 to SheetWrite(my_sheet1,"AI45:AJ72");
someSet_T_18 to SheetWrite(my_sheet1,"AK45:AL72");
someSet_T_19 to SheetWrite(my_sheet1,"AM45:AN72");
someSet_T_20 to SheetWrite(my_sheet1,"AO45:AP72");
someSet_T_21 to SheetWrite(my_sheet1,"AQ45:AR72");
someSet_T_22 to SheetWrite(my_sheet1,"AS45:AT72");
someSet_T_23 to SheetWrite(my_sheet1,"AU45:AV72");
someSet_T_24 to SheetWrite(my_sheet1,"AW45:AX72");
someSet_T_25 to SheetWrite(my_sheet1,"AY45:AZ72");
someSet_T_26 to SheetWrite(my_sheet1,"BA45:BB72");
someSet_T_27 to SheetWrite(my_sheet1,"BC45:BD72");
someSet_T_28 to SheetWrite(my_sheet1,"BE45:BF72");
someSet_T_29 to SheetWrite(my_sheet1,"BG45:BH72");
someSet_T_30 to SheetWrite(my_sheet1,"BI45:BJ72");


someSet_D_1 to SheetWrite(my_sheet1,"C82:D109");
someSet_D_2 to SheetWrite(my_sheet1,"E82:F109");
someSet_D_3 to SheetWrite(my_sheet1,"G82:H109");
someSet_D_4 to SheetWrite(my_sheet1,"I82:J109");
someSet_D_5 to SheetWrite(my_sheet1,"K82:L109");
someSet_D_6 to SheetWrite(my_sheet1,"M82:N109");
someSet_D_7 to SheetWrite(my_sheet1,"O82:P109");
someSet_D_8 to SheetWrite(my_sheet1,"Q82:R109");
someSet_D_9 to SheetWrite(my_sheet1,"S82:T109");
someSet_D_10 to SheetWrite(my_sheet1,"U82:V109");
someSet_D_11 to SheetWrite(my_sheet1,"W82:X109");
someSet_D_12 to SheetWrite(my_sheet1,"Y82:Z109");
someSet_D_13 to SheetWrite(my_sheet1,"AA82:AB109");
someSet_D_14 to SheetWrite(my_sheet1,"AC82:AD109");
someSet_D_15 to SheetWrite(my_sheet1,"AE82:AF109");

someSet_E_1 to SheetWrite(my_sheet,"A47:D51");
```

Appendix 8. DOCPLEX Code for the Multi-Objective Stochastic Programming Model

File sp_input.py

```
import os
import sqlite3

class input(object):
    def __init__(self):
        self.shopName()

    def shopName(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM shopname")
        rows = cur.fetchall()
        return rows

    def jobName(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM jobname")
        rows = cur.fetchall()
        return rows

    def partName(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM partname")
        rows = cur.fetchall()
        return rows

    def machineName(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM machinename")
        rows = cur.fetchall()
        return rows

    def jobDemand(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM jobDemand")
        rows = cur.fetchall()
        return rows

    def shopProp(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM shopProp")
        rows = cur.fetchall()
        return rows

    def shopMax(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM shopMax")
        rows = cur.fetchall()
        return rows

    def transDist(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM transDist")
        rows = cur.fetchall()
        return rows
```

```
    def transMax(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM transMax")
        rows = cur.fetchall()
        return rows

    def scenario1(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM dueScenario1")
        rows = cur.fetchall()
        return rows

    def scenario2(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM dueScenario2")
        rows = cur.fetchall()
        return rows

    def scenario3(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM dueScenario3")
        rows = cur.fetchall()
        return rows

    def scenario4(db_file):
        conn = sqlite3.connect(db_file)
        cur = conn.cursor()
        cur.execute("SELECT * FROM dueScenario4")
        rows = cur.fetchall()
        return rows

path = r".\Input.db"
shN = input.shopName(path)
jN = input.jobName(path)
pN = input.partName(path)
mN = input.machineName(path)
jDmd = input.jobDemand(path)
shProp = input.shopProp(path)
shMax = input.shopMax(path)
trDist = input.transDist(path)
trMax = input.transMax(path)
sc1 = input.scenario1(path)
sc2 = input.scenario2(path)
sc3 = input.scenario3(path)
sc4 = input.scenario4(path)
```

File sp_optModel.py

```
import numpy as np
import matplotlib.pyplot as plt
from docplex.mp.model import Model
from docplex.util.environment import get_environment
from collections import namedtuple
import sp_input as ip
import math

I = len(ip.shN) #qty of shops
J = len(ip.jN) #qty of jobs
K = len(ip.pN) #qty of parts
T = 28 #qty of days in timeline

shopID = [i for i in range(0,I)]
jobID = [i for i in range(0,J)]
partID = [i for i in range(0,K)]
```

```
timeID = [i for i in range(0,T)]

shopLst = ip.shN
jobLst = ip.jN
partLst = ip.pN
jobDmdLst = ip.jDmd
shopPropLst = ip.shProp
shopMaxLst = ip.shMax
trDistList = ip.trDist
trMaxLst = ip.trMax
sc1Lst = ip.sc1
sc2Lst = ip.sc2
sc3Lst = ip.sc3
sc4Lst = ip.sc4

proCost = [[a[6], a[7], a[8]] for a in shopPropLst]
proTime = [[a[3], a[4], a[5]] for a in shopPropLst]
transCost = [a[2] for a in shopPropLst]
transDist = [[a[1],a[2],a[3]] for a in trDistList]
proCostMax = [a[4] for a in shopMaxLst]
transCostMax = [a[2] for a in shopMaxLst]
transDistMax = [a[1] for a in trMaxLst]
demandQty = [[a[1],a[4],a[7],a[10],a[13],a[16],a[19],a[22],a[25],a[28]] for a in jobDmdLst]
dueDate = [[a[2]-1,a[5]-1,a[8]-1,a[11]-1,a[14]-1,a[17]-1,a[20]-1,a[23]-1,a[26]-1,a[29]-1] for a
in jobDmdLst]
delayCost = [[a[3],a[6],a[9],a[12],a[15],a[18],a[21],a[24],a[27],a[30]] for a in jobDmdLst]

sc1 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc1Lst]
sc2 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc2Lst]
sc3 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc3Lst]
sc4 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc4Lst]

dueDateSc = [sc1, sc2, sc3, sc4]
scKey = range(len(dueDateSc))

for s in range(0,len(dueDateSc)):
    for k in range(0,K):
        for j in range(0,J):
            if dueDateSc[s][k][j] == -1:
                dueDateSc[s][k][j] = 0

class optModel(object):
    def __init__(self, m='', pr1='', pr2='', pr3='', pr4=''):
        self.m = m
        self.n = 1-self.m

        self.pr1 = pr1
        self.pr2 = pr2
        self.pr3 = pr3
        self.pr4 = pr4
        self.prob = [self.pr1, self.pr2, self.pr3, self.pr4]

        A = [(i, j, k, t) for i in shopID for j in jobID for k in partID for t in timeID]
        A1 = [(i, j, k, t) for i in shopID for j in jobID for k in partID for t in range(0, 7)]
        A2 = [(s, i, j, k, t) for s in scKey for i in shopID for j in jobID for k in partID for t
in range(7, T)]
        B = [(j, k, t) for j in jobID for k in partID for t in timeID]
        B1 = [(j, k, t) for j in jobID for k in partID for t in range(0, 7)]
        B2 = [(s, j, k, t) for s in scKey for j in jobID for k in partID for t in range(7, T)]

        mdl = Model('prefSC')

        self.x1 = mdl.integer_var_dict(A1, name='Prod qty phase 1')
        self.x2 = mdl.integer_var_dict(A2, name='Prod qty phase 2')
        self.y1 = mdl.integer_var_dict(A1, name='Delv qty phase 1')
        self.y2 = mdl.integer_var_dict(A2, name='Delv qty phase 2')
        self.v1 = mdl.integer_var_dict(B1, name='Delay qty phase 1')
        self.v2 = mdl.integer_var_dict(B2, name='Delay qty phase 2')

        self.Tty1 = mdl.integer_var_dict(B1, name='Total transport qty phase 1')
        self.Tty2 = mdl.integer_var_dict(B2, name='Total transport qty phase 2')
```

```
        self.TtProCost1 = mdl.sum(
            proCost[k][i] * self.x1[i, j, k, t] for i in shopID for j in jobID for k in partID
for t in range(0, 7) if
            demandQty[k][j] != 0)
        self.TtProCost2 = mdl.sum(
            proCost[k][i] * self.x2[s, i, j, k, t] * self.prob[s] for i in shopID for j in jobID
for k in partID for t in
            range(7, T) for s in scKey if demandQty[k][j] != 0)
        self.TtTransCost1 = mdl.sum(
            transCost[k] * transDist[j][i] * self.y1[i, j, k, t] for i in shopID for j in jobID
for k in partID for t in
            range(0, 7) if demandQty[k][j] != 0)
        self.TtTransCost2 = mdl.sum(
            transCost[k] * transDist[j][i] * self.y2[s, i, j, k, t] * self.prob[s] for i in
shopID for j in jobID for k in partID
            for t in range(7, T) for s in scKey if demandQty[k][j] != 0)
        self.TtTardyCost1 = mdl.sum(
            delayCost[k][j] * self.v1[j, k, t] for j in jobID for k in partID for t in range(0,
7) if demandQty[k][j] != 0)
        self.TtTardyCost2 = mdl.sum(
            delayCost[k][j] * self.v2[s, j, k, t] * self.prob[s] for j in jobID for k in partID
for t in range(7, T) for s in
            scKey if demandQty[k][j] != 0)
        self.TtRemainPro = mdl.sum(
            proCostMax[k] * self.v2[s, j, k, T - 1] * self.prob[s] for j in jobID for k in partID
for s in scKey if
            demandQty[k][j] != 0)
        self.TtRemainTrans = mdl.sum(
            transCostMax[k] * transDistMax[j] * self.v2[s, j, k, T - 1] * self.prob[s] for j in
jobID for k in partID for s in
            scKey if demandQty[k][j] != 0)
        self.TtDelay1 = mdl.sum(self.v1[j,k,t] for j in jobID for k in partID for t in range(0,7)
if demandQty[k][j] != 0)
        self.TtDelay2 = mdl.sum(self.v2[s,j,k,t] * self.prob[s] for j in jobID for k in partID
for t in range(7,T) for s in scKey if demandQty[k][j] != 0)

        self.TtProCost = self.TtProCost1 + self.TtProCost2
        self.TtTransCost = self.TtTransCost1 + self.TtTransCost2
        self.TtTardyCost = self.TtTardyCost1 + self.TtTardyCost2
        self.TtDelay = self.TtDelay1 + self.TtDelay2
        self.TtCost = self.TtProCost + self.TtTransCost + self.TtTardyCost + self.TtRemainPro +
self.TtRemainTrans

        mdl.minimize(self.m * self.TtCost + self.n * self.TtDelay)

        # constraint about machine availability
        mdl.add_constraints(
            mdl.sum(proTime[k][i] * self.x1[i, j, k, t] for j in jobID if demandQty[k][j] != 0)
<= 16 for i in shopID for k
            in partID for t in range(0, 7))
        mdl.add_constraints(
            mdl.sum(proTime[k][i] * self.x2[s, i, j, k, t] for j in jobID if demandQty[k][j] !=
0) <= 16 for i in shopID for
            k in partID for t in range(7, T) for s in scKey)

        # constraint about tardy before due date ################################
        mdl.add_constraints(
            self.v1[j, k, t] == 0 for j in jobID for k in partID for t in range(0, 7) for s in
scKey if t < dueDateSc[s][k][j] if
            demandQty[k][j] != 0)
        mdl.add_constraints(self.v2[s, j, k, t] == 0 for j in jobID for k in partID for t in
range(7, T) for s in scKey if
                            t < dueDateSc[s][k][j] if demandQty[k][j] != 0)
        # constraint about tardy after due date
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in timeID if h <= t if
demandQty[k][j] != 0) + self.v1[j, k, t] ==
            demandQty[k][j] for j in jobID for k in partID for t in range(0, 7) for s in scKey if
t >= dueDateSc[s][k][j] if
            demandQty[k][j] != 0)
```

```
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, 7) if h <= t if
demandQty[k][j] != 0) + mdl.sum(
                self.y2[s, i, j, k, h] for i in shopID for h in range(7, T) if h <= t if
demandQty[k][j] != 0) + self.v2[
                s, j, k, t] == demandQty[k][j] for j in jobID for k in partID for t in range(7,
T) for s in scKey if
            t >= dueDateSc[s][k][j] if demandQty[k][j] != 0)


        # constraint about transportation 1
        mdl.add_constraints(mdl.sum(self.y1[i, j, k, t1] for t1 in range(0, 7)) + mdl.sum(
            self.y2[s, i, j, k, t2] for t2 in range(7, T)) == mdl.sum(self.x1[i, j, k, t1] for t1
in range(0, 7)) + mdl.sum(
            self.x2[s, i, j, k, t2] for t2 in range(7, T)) for i in shopID for j in jobID for k
in partID for s in scKey if
                            demandQty[k][j] != 0)

        # constraint about transportation 2
        mdl.add_constraints(
            mdl.sum(self.x1[i, j, k, h] for h in range(0, t+1)) >= sum(self.y1[i, j, k, h] for h
in range(0, t+1)) for i in shopID for
            j in jobID for k in partID for t in range(0, 7) if demandQty[k][j] != 0)
        mdl.add_constraints(
            mdl.sum(self.x1[i, j, k, h] for h in range(0, 7)) + mdl.sum(self.x2[s, i, j, k, h]
for h in range(7, t+1)) >= mdl.sum(
                self.y1[i, j, k, h] for h in range(0, 7)) + mdl.sum(self.y2[s, i, j, k, h] for h
in range(7, t+1)) for i in shopID
            for j in jobID for k in partID for t in range(7, T) for s in scKey if demandQty[k][j]
!= 0)

        # constraint about total transportation
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, t+1)) == self.Tty1[j,
k, t] for
            j in jobID for k in partID for t in range(0, 7) if demandQty[k][j] != 0)
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, 7)) +
mdl.sum(self.y2[s, i, j, k, h] for i in shopID for h in range(7, t+1)) == self.Tty2[s, j, k, t]
            for j in jobID for k in partID for t in range(7, T) for s in scKey if demandQty[k][j]
!= 0)


        mdl.parameters.timelimit = 120
        self.solution = mdl.solve(log_output=False)
        self.solution.solve_status
        #self.solution.objective_value

        ####SCHEDULE SOLUTION
        self.sol_Pro1 = self.solution.get_value_dict(self.x1, keep_zeros=True, precision=1e-1)
        self.sol_Pro2 = self.solution.get_value_dict(self.x2, keep_zeros=True, precision=1e-1)
        self.sol_Dlv1 = self.solution.get_value_dict(self.y1, keep_zeros=True, precision=1e-1)
        self.sol_Dlv2 = self.solution.get_value_dict(self.y2, keep_zeros=True, precision=1e-1)
        self.sol_Dly1 = self.solution.get_value_dict(self.v1, keep_zeros=True, precision=1e-1)
        self.sol_Dly2 = self.solution.get_value_dict(self.v2, keep_zeros=True, precision=1e-1)
        self.sol_TotalDlv1 = self.solution.get_value_dict(self.Tty1, keep_zeros=True,
precision=1e-1)
        self.sol_TotalDlv2 = self.solution.get_value_dict(self.Tty2, keep_zeros=True,
precision=1e-1)

        self.sol_TtProCost = math.trunc(self.solution.get_value(self.TtProCost))
        self.sol_TtTransCost = math.trunc(self.solution.get_value(self.TtTransCost))
        self.sol_TtTardyCost = math.trunc(self.solution.get_value(self.TtTardyCost))
        self.sol_TtRemainPro = math.trunc(self.solution.get_value(self.TtRemainPro))
        self.sol_TtRemainTrans = math.trunc(self.solution.get_value(self.TtRemainTrans))
        self.sol_TtCost = math.trunc(self.solution.get_value(self.TtCost))
        self.sol_TtDelay = self.solution.get_value(self.TtDelay)

    def optSolution(self):
        print(self.solution.solve_status)
        #print(self.solution.objective_value)
```

```
        print('Total cost ',self.solution.get_value(self.TtCost))
        print('Total delay ',self.solution.get_value(self.TtDelay))
        #print('Multi objective value [TtotalCost, TtDelay]',solution.multi_objective_values)

    def solTtTran1(self):
        lst = self.sol_TotalDlv1
        for j in jobID:
            for k in partID:
                for t in range(0,7):
                    if demandQty[k][j] != 0:
                        print(j, k, t, self.solution.get_value(self.Tty1[j, k, t]))
        return lst

    def solTtTran2(self):
        lst = self.sol_TotalDlv2
        return lst

    def solTtCost(self):
        a = self.sol_TtCost
        return a

    def solTtDelay(self):
        b = self.sol_TtDelay
        return b

    def solTtCost_TtDelay(self):
        a = round(self.solution.get_value(self.TtCost),0)
        b = self.solution.get_value(self.TtDelay)
        r = [a,b]
        return r

    def solTtProCost(self):
        r = self.sol_TtProCost
        return r

    def solTtTransCost(self):
        r = self.sol_TtTransCost
        return r

    def solTtTardyCost(self):
        r = self.sol_TtTardyCost
        return r

    def solTtRemainPro(self):
        r = self.sol_TtRemainPro
        return r

    def solTtRemainTrans(self):
        r = self.sol_TtRemainTrans
        return r

    def solSchedule(self):
        print('Produced Qty for first week ',self.sol_Pro1)
        print('Produced Qty for 3 weeks lookahead ',self.sol_Pro1)
        print('Delivery Qty for first week ',self.sol_Dlv1)
        print('Delivery Qty for 3 weeks lookahead ',self.sol_Dlv2)
        print('Delay Qty for first week ',self.sol_Dly1)
        print('Delay Qty for 3 weeks lookahead ', self.sol_Dly2)

    def demandQtyEndWeek1(self):
        lst = [[0]*J]*K
        for j in jobID:
            for k in partID:
                finishQty = 0
                if demandQty[k][j] != 0:
                    for i in shopID:
                        for t in range(0,7):
                            finishQty = finishQty + self.sol_Pro1.get((i,j,k,t),'')
                lst[k][j] = demandQty[k][j]-finishQty
                #print('Demand Qty End of Week 1 ', k, j, lst[k][j])
        return lst
```

```
    def handlingCost(self):
        avgCost = [0]*K
        unitHandlingCost = [0]*K
        hdlCost = 0
        remainQty = self.demandQtyEndWeek1()
        for k in partID:
            cost = 0
            for i in shopID:
                cost = cost + proCost[k][i]
            avgCost[k] = cost/I
            unitHandlingCost[k] = 0.15*avgCost[k]
            #print('Unit handling cost item ',k, unitHandlingCost[k])

        for j in jobID:
            for k in partID:
                if demandQty[k][j] != 0:
                    if dueDateSc[0][k][j] != dueDate[k][j]:  ############Use the scenario 0 so
this could apply for the single scenario cases to run the evaluation on handling cost
                        hdlCost = hdlCost + unitHandlingCost[k]*remainQty[k][j]
                        #print('Unit handling cost ', k, j, hdlCost)
        HdlCost = math.trunc(hdlCost)
        #print('Total handling cost ', HdlCost)
        return HdlCost

    def test(self):
        test_TtProCost = 0
        test_TtTransCost = 0
        test_TtTardyCost = 0
        test_TtRemainPro = 0
        test_TtRemainTrans = 0
        real_TtTardyCost = 0

        test_TtProCost_eachSc = [0] * len(dueDateSc)
        test_TtTransCost_eachSc = [0] * len(dueDateSc)
        test_TtTardyCost_eachSc = [0] * len(dueDateSc)
        test_TtRemainPro_eachSc = [0] * len(dueDateSc)
        test_TtRemainTrans_eachSc = [0] * len(dueDateSc)
        test_TtCost_eachSc = [0] * len(dueDateSc)
        real_TtTardyCost_eachSc = [0] * len(dueDateSc)
        real_TtCost_eachSc = [0] * len(dueDateSc)

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(0, 7):
                        if demandQty[k][j] != 0:
                            test_TtProCost = test_TtProCost + proCost[k][i] *
self.sol_Pro1.get((i, j, k, t), '')
                            test_TtTransCost = test_TtTransCost + transCost[k] * transDist[j][i]
* self.sol_Dlv1.get(
                                (i, j, k, t), '')

        for j in jobID:
            for k in partID:
                for t in range(0,7):
                    if demandQty[k][j] != 0:
                        test_TtTardyCost = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly1.get((j, k, t), '')

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(0, 7):
                        for s in scKey:
                            if demandQty[k][j] != 0:
                                test_TtProCost_eachSc[s] = test_TtProCost + proCost[k][i] *
self.sol_Pro1.get((i, j, k, t),

'')
                                test_TtTransCost_eachSc[s] = test_TtTransCost + transCost[k] *
```

```
transDist[j][
                                    i] * self.sol_Dlv1.get((i, j, k, t), '')
        for j in jobID:
            for k in partID:
                for t in range(0,7):
                    for s in scKey:
                        if demandQty[k][j] != 0:
                            test_TtTardyCost_eachSc[s] = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly1.get((j, k, t), '')
                            if t >= dueDate[k][j]:
                                if demandQty[k][j] > self.sol_TotalDlv1.get((j, k, t), ''):
                                    real_TtTardyCost_eachSc[s] = test_TtTardyCost +
delayCost[k][j]*(demandQty[k][j]-self.sol_TotalDlv1.get((j, k, t), ''))

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(7, T):
                        for s in scKey:
                            if demandQty[k][j] != 0:
                                test_TtProCost = test_TtProCost + proCost[k][i] *
self.sol_Pro2.get((s, i, j, k, t), '') * \
                                                 self.prob[s]
                                test_TtTransCost = test_TtTransCost + transCost[k] *
transDist[j][i] * self.sol_Dlv2.get(
                                    (s, i, j, k, t), '') * self.prob[s]

                                test_TtProCost_eachSc[s] = test_TtProCost_eachSc[s] +
proCost[k][i] * self.sol_Pro2.get(
                                    (s, i, j, k, t), '')
                                test_TtTransCost_eachSc[s] = test_TtTransCost_eachSc[s] +
transCost[k] * transDist[j][
                                    i] * self.sol_Dlv2.get((s, i, j, k, t), '')

        for j in jobID:
            for k in partID:
                for t in range(7,T):
                    for s in scKey:
                        if demandQty[k][j] != 0:
                            test_TtTardyCost = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly2.get((s, j, k, t),'') * self.prob[s]
                            test_TtTardyCost_eachSc[s] = test_TtTardyCost_eachSc[s] +
delayCost[k][j] * self.sol_Dly2.get((s, j, k, t), '')
                            if t >= dueDateSc[s][k][j]:
                                if demandQty[k][j] > self.sol_TotalDlv2.get((s,j, k, t), ''):
                                    #################### REMEMBER TO CHANGE SCENARIO FOR
self.sol_TotalDlv2.get((0,j, k, t), '')) FROM 0 TO 1 OR 2 OR 3 DEPENDING ON THE CONSIDERED
SCENARIO
                                    real_TtTardyCost_eachSc[s] = real_TtTardyCost_eachSc[s] +
delayCost[k][j]*(demandQty[k][j]-self.sol_TotalDlv2.get((0,j, k, t), ''))

        for j in jobID:
            for k in partID:
                for s in scKey:
                    test_TtRemainPro = test_TtRemainPro + proCostMax[k] * self.sol_Dly2.get((s,
j, k, T - 1), '') * self.prob[s]
                    test_TtRemainTrans = test_TtRemainTrans + transCostMax[k] * transDistMax[j] *
self.sol_Dly2.get(
                        (s, j, k, T - 1), '') * self.prob[s]

                    test_TtRemainPro_eachSc[s] = test_TtRemainPro + proCostMax[k] *
self.sol_Dly2.get((s, j, k, T - 1), '')
                    test_TtRemainTrans_eachSc[s] = test_TtRemainTrans + transCostMax[k] *
transDistMax[
                        j] * self.sol_Dly2.get((s, j, k, T - 1), '')

        for s in scKey:
            test_TtCost_eachSc[s] = round(
                test_TtProCost_eachSc[s] + test_TtTransCost_eachSc[s] +
test_TtTardyCost_eachSc[s] +
                test_TtRemainPro_eachSc[s] + test_TtRemainTrans_eachSc[s], 2)
```

```
            real_TtCost_eachSc[s] = round(
                self.sol_TtProCost + self.sol_TtTransCost + real_TtTardyCost_eachSc[s] +
                self.sol_TtRemainPro + self.sol_TtRemainTrans, 2)

        print('sol vs Test TtProCost ', self.sol_TtProCost, round(test_TtProCost, 2))
        print('sol vs Test TtTransCost ', self.sol_TtTransCost, round(test_TtTransCost, 2))
        print('sol vs Test TtTardyCost ', self.sol_TtTardyCost, round(test_TtTardyCost, 2))
        print('sol vs Test TtRemainPro ', self.sol_TtRemainPro, round(test_TtRemainPro, 2))
        print('sol vs Test TtRemainTrans ', self.sol_TtRemainTrans, round(test_TtRemainTrans, 2))
        print('TotalCost_allScenarios vs TotalCost_eachScenario ', round(self.sol_TtCost, 2),
test_TtCost_eachSc)
        print('TotalCost_allScenarios vs TotalCost_REAL ', round(self.sol_TtCost, 2),
real_TtCost_eachSc)
        print('Total REAL Tardy Cost each Scenario ', real_TtTardyCost_eachSc)


#optModel(0.5,1,0,0,0).optSolution()
#a = optModel(1,1,0,0,0)
#a.test()
b = optModel(0.05,0.4,0.3,0.1,0.2)
b.optSolution()
#a.demandQtyEndWeek1()
#a.handlingCost()
#print('handling cost if no change in schedule is: ',optModel(1,1,0,0,0).handlingCost())
#print(optModel(1).solTtCost_TtDelay())
#print(optModel(1,1,0,0,0).solTtCost())
#print(optModel(1,1,0,0,0).solTtTran1())
```

File sp_table_Prod_allSc.py

```
import xlwt
import sys
from PyQt5.QtWidgets import QMainWindow, QApplication, QWidget, QAction, QTableWidget,
QTableWidgetItem, QVBoxLayout, QFileDialog
from PyQt5.QtGui import QIcon
from PyQt5.QtCore import pyqtSlot
from PyQt5 import QtGui
import sp_input as ip
import sp_optModel as opt

class App(QWidget):

    def __init__(self):
        super().__init__()
        self.title = 'Production Schedule All Scenarios'
        self.left = 50
        self.top = 50
        self.width = 1700
        self.height = 950
        self.initUI()

    def initUI(self):
        self.setWindowTitle(self.title)
        self.setGeometry(self.left, self.top, self.width, self.height)

        self.createTable()

        # Add box layout, add table to box layout and add box layout to widget
        self.layout = QVBoxLayout()
        self.layout.addWidget(self.tableWidget)
        self.setLayout(self.layout)

        # Show widget
        self.show()

    def createTable(self):
        # Create table
        lgSh = len(ip.shN)
```

```
        lgJ = len(ip.jN)
        lgP = len(ip.pN)
        T = 28
        lgSc = len(opt.scKey)
        self.rowC = 1 + lgP * lgJ * lgSh * lgSc
        self.colC = 4+T+5
        self.tableWidget = QTableWidget()
        self.tableWidget.setRowCount(self.rowC)
        self.tableWidget.setColumnCount(self.colC)
        self.tableWidget.setColumnWidth(0, 60)
        self.tableWidget.setColumnWidth(1, 60)
        self.tableWidget.setColumnWidth(2, 60)
        self.tableWidget.setColumnWidth(3, 80)
        for i in range(0,T):
            self.tableWidget.setColumnWidth(i+4,40)
        self.tableWidget.setColumnWidth(4+T, 70)
        self.tableWidget.setColumnWidth(4+T+1, 70)
        self.tableWidget.setColumnWidth(4+T+2, 70)
        self.tableWidget.setColumnWidth(4+T+3, 70)
        self.tableWidget.setColumnWidth(4+T+4, 70)
        for i in range(0,self.rowC):
            self.tableWidget.setRowHeight(i,17)

        self.tableWidget.setItem(0, 0, QTableWidgetItem("Shop"))
        self.tableWidget.setItem(0, 1, QTableWidgetItem("Job"))
        self.tableWidget.setItem(0, 2, QTableWidgetItem("Part"))
        self.tableWidget.setItem(0, 3, QTableWidgetItem("Scenario"))
        for i in range(4, 4+T):
            self.tableWidget.setItem(0, i, QTableWidgetItem('D ' + str(i-3)))
        self.tableWidget.setItem(0, 4+T, QTableWidgetItem("Sum produced"))
        self.tableWidget.setItem(0, 4+T+1, QTableWidgetItem("Sum delivered"))
        self.tableWidget.setItem(0, 4+T+2, QTableWidgetItem("Sum all shops"))
        self.tableWidget.setItem(0, 4+T+3, QTableWidgetItem("Demand qty"))
        self.tableWidget.setItem(0, 4+T+4, QTableWidgetItem("Due date"))

        m = 1
        prb1 = 0.4
        prb2 = 0.3
        prb3 = 0.1
        prb4 = 0.2
        OPT = opt.optModel(m, prb1, prb2, prb3, prb4)

        for s in range(0, lgSc):
            for i in range(0, lgSh):
                for j in range(0, lgJ):
                    for k in range(0, lgP):
                        pr = 0
                        dlv = 0
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + 1, 0,
QTableWidgetItem('Shop ' + str(i + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + 1, 1,
QTableWidgetItem('Job ' + str(j + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc * k
+ 1, 2, QTableWidgetItem('Part ' + str(k + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc * k
+ s + 1, 3, QTableWidgetItem('Sc ' + str(s + 1)))
                        if ip.jDmd[k][j * 3 + 1] != 0:
                            self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T +
3,
                                                     QTableWidgetItem(str(ip.jDmd[k][j * 3 + 1])))   #
Demand quantity
                        if opt.dueDateSc[s][k][j] != 0:
                            self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T +
4,
                                                     QTableWidgetItem(str(opt.dueDateSc[s][k][j]+1)))
# Due date
                        for t in range(0,7):
                            if OPT.sol_Pro1.get((i,j,k,t),'') != 0:
                                self.tableWidget.setItem(i*lgSc*lgP*lgJ+lgSc*lgP*j+lgSc*k+s+1,
t+4, QTableWidgetItem(str(round(OPT.sol_Pro1.get((i,j,k,t),'')))))
                                pr = pr+OPT.sol_Pro1.get((i,j,k,t),'')
```

```
                            if OPT.sol_Dlv1.get((i,j,k,t),'') != 0: #total delivered quantity
                                dlv = dlv+OPT.sol_Dlv1.get((i,j,k,t),'')
                        for t in range(7,T):
                            if OPT.sol_Pro2.get((s,i,j,k,t),'') != 0:
                                self.tableWidget.setItem(i*lgSc*lgP*lgJ+lgSc*lgP*j+lgSc*k+s+1,
t+4, QTableWidgetItem(str(round(OPT.sol_Pro2.get((s,i,j,k,t),'')))))
                                pr = pr+OPT.sol_Pro2.get((s,i,j,k,t),'')
                            if OPT.sol_Dlv2.get((s,i,j,k,t),'') != 0: #total delivered quantity
                                dlv = dlv+OPT.sol_Dlv2.get((s,i,j,k,t),'')

                        if pr != 0:
                            self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc
* k + s + 1, 4 + T, QTableWidgetItem(str(round(pr)))) #Total production quantity
                        if dlv != 0:
                            self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc
* k + s + 1, 4 + T + 1, QTableWidgetItem(str(round(dlv)))) #Total deliver quantity
        for s in range(0, lgSc):
            for j in range(0, lgJ):
                for k in range(0,lgP):
                    A = 0
                    for t in range(0,7):
                        for i in range(0,lgSh):
                            A = A + OPT.sol_Pro1.get((i,j,k,t),'')
                    for t in range(7,T):
                        for i in range(0,lgSh):
                            A = A + OPT.sol_Pro2.get((s,i,j,k,t),'')
                    if A !=0:
                        self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T + 2,
QTableWidgetItem(str(round(A)))) #Sum production quantity of all shops

        # table selection change
        self.tableWidget.doubleClicked.connect(self.on_click)

        # save data to a excel file
        filename = QFileDialog.getSaveFileName(self, 'Save File', '', ".xls(*.xls)")
        wbk = xlwt.Workbook()
        sheet = wbk.add_sheet('ProdSch_allSC', cell_overwrite_ok=True)
        for i in range(0,self.rowC):
            for j in range(0,self.colC):
                if self.tableWidget.item(i,j) != None:
                    mycell = self.tableWidget.item(i,j).text()
                    sheet.write(i,j,mycell)
        wbk.save(filename[0])

    @pyqtSlot()

    def on_click(self):
        print("\n")
        for currentQTableWidgetItem in self.tableWidget.selectedItems():
            print(currentQTableWidgetItem.row(), currentQTableWidgetItem.column(),
currentQTableWidgetItem.text())


if __name__ == '__main__':
    app = QApplication(sys.argv)
    ex = App()
    sys.exit(app.exec_())
```

File sp_optModel_Single_Sc.py

```
import numpy as np
import matplotlib.pyplot as plt
from docplex.mp.model import Model
from docplex.util.environment import get_environment
from collections import namedtuple
import sp_input as ip
import math
```

```
I = len(ip.shN) #qty of shops
J = len(ip.jN) #qty of jobs
K = len(ip.pN) #qty of parts
T = 28 #qty of days in timeline

shopID = [i for i in range(0,I)]
jobID = [i for i in range(0,J)]
partID = [i for i in range(0,K)]
timeID = [i for i in range(0,T)]

shopLst = ip.shN
jobLst = ip.jN
partLst = ip.pN
jobDmdLst = ip.jDmd
shopPropLst = ip.shProp
shopMaxLst = ip.shMax
trDistList = ip.trDist
trMaxLst = ip.trMax
sc1Lst = ip.sc1
sc2Lst = ip.sc2
sc3Lst = ip.sc3
sc4Lst = ip.sc4

proCost = [[a[6], a[7], a[8]] for a in shopPropLst]
proTime = [[a[3], a[4], a[5]] for a in shopPropLst]
transCost = [a[2] for a in shopPropLst]
transDist = [[a[1],a[2],a[3]] for a in trDistList]
proCostMax = [a[4] for a in shopMaxLst]
transCostMax = [a[2] for a in shopMaxLst]
transDistMax = [a[1] for a in trMaxLst]
demandQty = [[a[1],a[4],a[7],a[10],a[13],a[16],a[19],a[22],a[25],a[28]] for a in jobDmdLst]
dueDate = [[a[2]-1,a[5]-1,a[8]-1,a[11]-1,a[14]-1,a[17]-1,a[20]-1,a[23]-1,a[26]-1,a[29]-1] for a
in jobDmdLst]
delayCost = [[a[3],a[6],a[9],a[12],a[15],a[18],a[21],a[24],a[27],a[30]] for a in jobDmdLst]

sc1 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc1Lst]
sc2 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc2Lst]
sc3 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc3Lst]
sc4 = [[a[1]-1,a[2]-1,a[3]-1,a[4]-1,a[5]-1,a[6]-1,a[7]-1,a[8]-1,a[9]-1,a[10]-1] for a in sc4Lst]

#dueDateSc = [sc1, sc2, sc3, sc4]
dueDateSc = [sc1]
scKey = range(len(dueDateSc))

for s in range(0,len(dueDateSc)):
    for k in range(0,K):
        for j in range(0,J):
            if dueDateSc[s][k][j] == -1:
                dueDateSc[s][k][j] = 0

class optModel(object):
    def __init__(self, m='', pr1='', pr2='', pr3='', pr4=''):
        self.m = m
        self.n = 1-self.m

        self.pr1 = pr1
        self.pr2 = pr2
        self.pr3 = pr3
        self.pr4 = pr4
        self.prob = [self.pr1, self.pr2, self.pr3, self.pr4]

        A = [(i, j, k, t) for i in shopID for j in jobID for k in partID for t in timeID]
        A1 = [(i, j, k, t) for i in shopID for j in jobID for k in partID for t in range(0, 7)]
        A2 = [(s, i, j, k, t) for s in scKey for i in shopID for j in jobID for k in partID for t
in range(7, T)]
        B = [(j, k, t) for j in jobID for k in partID for t in timeID]
        B1 = [(j, k, t) for j in jobID for k in partID for t in range(0, 7)]
        B2 = [(s, j, k, t) for s in scKey for j in jobID for k in partID for t in range(7, T)]

        mdl = Model('prefSC')
```

```
        self.x1 = mdl.integer_var_dict(A1, name='Prod qty phase 1')
        self.x2 = mdl.integer_var_dict(A2, name='Prod qty phase 2')
        self.y1 = mdl.integer_var_dict(A1, name='Delv qty phase 1')
        self.y2 = mdl.integer_var_dict(A2, name='Delv qty phase 2')
        self.v1 = mdl.integer_var_dict(B1, name='Delay qty phase 1')
        self.v2 = mdl.integer_var_dict(B2, name='Delay qty phase 2')

        self.Tty1 = mdl.integer_var_dict(B1, name='Total transport qty phase 1')
        self.Tty2 = mdl.integer_var_dict(B2, name='Total transport qty phase 2')

        self.TtProCost1 = mdl.sum(
            proCost[k][i] * self.x1[i, j, k, t] for i in shopID for j in jobID for k in partID
for t in range(0, 7) if
            demandQty[k][j] != 0)
        self.TtProCost2 = mdl.sum(
            proCost[k][i] * self.x2[s, i, j, k, t] * self.prob[s] for i in shopID for j in jobID
for k in partID for t in
            range(7, T) for s in scKey if demandQty[k][j] != 0)
        self.TtTransCost1 = mdl.sum(
            transCost[k] * transDist[j][i] * self.y1[i, j, k, t] for i in shopID for j in jobID
for k in partID for t in
            range(0, 7) if demandQty[k][j] != 0)
        self.TtTransCost2 = mdl.sum(
            transCost[k] * transDist[j][i] * self.y2[s, i, j, k, t] * self.prob[s] for i in
shopID for j in jobID for k in partID
            for t in range(7, T) for s in scKey if demandQty[k][j] != 0)
        self.TtTardyCost1 = mdl.sum(
            delayCost[k][j] * self.v1[j, k, t] for j in jobID for k in partID for t in range(0,
7) if demandQty[k][j] != 0)
        self.TtTardyCost2 = mdl.sum(
            delayCost[k][j] * self.v2[s, j, k, t] * self.prob[s] for j in jobID for k in partID
for t in range(7, T) for s in
            scKey if demandQty[k][j] != 0)
        self.TtRemainPro = mdl.sum(
            proCostMax[k] * self.v2[s, j, k, T - 1] * self.prob[s] for j in jobID for k in partID
for s in scKey if
            demandQty[k][j] != 0)
        self.TtRemainTrans = mdl.sum(
            transCostMax[k] * transDistMax[j] * self.v2[s, j, k, T - 1] * self.prob[s] for j in
jobID for k in partID for s in
            scKey if demandQty[k][j] != 0)
        self.TtDelay1 = mdl.sum(self.v1[j,k,t] for j in jobID for k in partID for t in range(0,7)
if demandQty[k][j] != 0)
        self.TtDelay2 = mdl.sum(self.v2[s,j,k,t] * self.prob[s] for j in jobID for k in partID
for t in range(7,T) for s in scKey if demandQty[k][j] != 0)

        self.TtProCost = self.TtProCost1 + self.TtProCost2
        self.TtTransCost = self.TtTransCost1 + self.TtTransCost2
        self.TtTardyCost = self.TtTardyCost1 + self.TtTardyCost2
        self.TtDelay = self.TtDelay1 + self.TtDelay2
        self.TtCost = self.TtProCost + self.TtTransCost + self.TtTardyCost + self.TtRemainPro +
self.TtRemainTrans

        mdl.minimize(self.m * self.TtCost + self.n * self.TtDelay)

        # constraint about machine availability
        mdl.add_constraints(
            mdl.sum(proTime[k][i] * self.x1[i, j, k, t] for j in jobID if demandQty[k][j] != 0)
<= 16 for i in shopID for k
            in partID for t in range(0, 7))
        mdl.add_constraints(
            mdl.sum(proTime[k][i] * self.x2[s, i, j, k, t] for j in jobID if demandQty[k][j] !=
0) <= 16 for i in shopID for
            k in partID for t in range(7, T) for s in scKey)

        # constraint about tardy before due date #################################
        mdl.add_constraints(
            self.v1[j, k, t] == 0 for j in jobID for k in partID for t in range(0, 7) if t <
dueDate[k][j] if
            demandQty[k][j] != 0)
```

```
        mdl.add_constraints(self.v2[s, j, k, t] == 0 for j in jobID for k in partID for t in
range(7, T) for s in scKey if
                            t < dueDateSc[s][k][j] if demandQty[k][j] != 0)
        # constraint about tardy after due date
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in timeID if h <= t if
demandQty[k][j] != 0) + self.v1[j, k, t] ==
            demandQty[k][j] for j in jobID for k in partID for t in range(0, 7) if t >=
dueDate[k][j] if
            demandQty[k][j] != 0)
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, 7) if h <= t if
demandQty[k][j] != 0) + mdl.sum(
                self.y2[s, i, j, k, h] for i in shopID for h in range(7, T) if h <= t if
demandQty[k][j] != 0) + self.v2[
                s, j, k, t] == demandQty[k][j] for j in jobID for k in partID for t in range(7,
T) for s in scKey if
            t >= dueDateSc[s][k][j] if demandQty[k][j] != 0)

        # constraint about transportation 1
        mdl.add_constraints(mdl.sum(self.y1[i, j, k, t1] for t1 in range(0, 7)) + mdl.sum(
            self.y2[s, i, j, k, t2] for t2 in range(7, T)) == mdl.sum(self.x1[i, j, k, t1] for t1
in range(0, 7)) + mdl.sum(
            self.x2[s, i, j, k, t2] for t2 in range(7, T)) for i in shopID for j in jobID for k
in partID for s in scKey if
                            demandQty[k][j] != 0)

        # constraint about transportation 2
        mdl.add_constraints(
            mdl.sum(self.x1[i, j, k, h] for h in range(0, t)) >= sum(self.y1[i, j, k, h] for h in
range(0, t)) for i in shopID for
            j in jobID for k in partID for t in range(0, 7) if demandQty[k][j] != 0)
        mdl.add_constraints(
            mdl.sum(self.x1[i, j, k, h] for h in range(0, 7)) + mdl.sum(self.x2[s, i, j, k, h]
for h in range(7, t)) >= mdl.sum(
                self.y1[i, j, k, h] for h in range(0, 7)) + mdl.sum(self.y2[s, i, j, k, h] for h
in range(7, t)) for i in shopID
            for j in jobID for k in partID for t in range(7, T) for s in scKey if demandQty[k][j]
!= 0)

        # constraint about total transportation
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, t+1)) == self.Tty1[j,
k, t] for
            j in jobID for k in partID for t in range(0, 7) if demandQty[k][j] != 0)
        mdl.add_constraints(
            mdl.sum(self.y1[i, j, k, h] for i in shopID for h in range(0, 7)) +
mdl.sum(self.y2[s, i, j, k, h] for i in shopID for h in range(7, t+1)) == self.Tty2[s, j, k, t]
            for j in jobID for k in partID for t in range(7, T) for s in scKey if demandQty[k][j]
!= 0)

        mdl.parameters.timelimit = 120
        self.solution = mdl.solve(log_output=False)
        self.solution.solve_status
        #self.solution.objective_value

        ####SCHEDULE SOLUTION
        self.sol_Pro1 = self.solution.get_value_dict(self.x1, keep_zeros=True, precision=1e-1)
        self.sol_Pro2 = self.solution.get_value_dict(self.x2, keep_zeros=True, precision=1e-1)
        self.sol_Dlv1 = self.solution.get_value_dict(self.y1, keep_zeros=True, precision=1e-1)
        self.sol_Dlv2 = self.solution.get_value_dict(self.y2, keep_zeros=True, precision=1e-1)
        self.sol_Dly1 = self.solution.get_value_dict(self.v1, keep_zeros=True, precision=1e-1)
        self.sol_Dly2 = self.solution.get_value_dict(self.v2, keep_zeros=True, precision=1e-1)
        self.sol_TotalDlv1 = self.solution.get_value_dict(self.Tty1, keep_zeros=True,
precision=1e-1)
        self.sol_TotalDlv2 = self.solution.get_value_dict(self.Tty2, keep_zeros=True,
precision=1e-1)

        self.sol_TtProCost = math.trunc(self.solution.get_value(self.TtProCost))
        self.sol_TtTransCost = math.trunc(self.solution.get_value(self.TtTransCost))
        self.sol_TtTardyCost = math.trunc(self.solution.get_value(self.TtTardyCost))
```

```
    self.sol_TtRemainPro = math.trunc(self.solution.get_value(self.TtRemainPro))
    self.sol_TtRemainTrans = math.trunc(self.solution.get_value(self.TtRemainTrans))
    self.sol_TtCost = math.trunc(self.solution.get_value(self.TtCost))
    self.sol_TtDelay = self.solution.get_value(self.TtDelay)

def optSolution(self):
    print(self.solution.solve_status)
    #print(self.solution.objective_value)
    print('Total cost ',self.solution.get_value(self.TtCost))
    print('Total delay ',self.solution.get_value(self.TtDelay))
    #print('Multi objective value [TtotalCost, TtDelay]',solution.multi_objective_values)

def solTtTran1(self):
    lst = self.sol_TotalDlv1
    for j in jobID:
        for k in partID:
            for t in range(0,7):
                if demandQty[k][j] != 0:
                    print(j, k, t, self.solution.get_value(self.Tty1[j, k, t]))
    return lst

def solTtTran2(self):
    lst = self.sol_TotalDlv2
    return lst

def solTtCost(self):
    a = self.sol_TtCost
    return a

def solTtDelay(self):
    b = self.sol_TtDelay
    return b

def solTtCost_TtDelay(self):
    a = round(self.solution.get_value(self.TtCost),0)
    b = self.solution.get_value(self.TtDelay)
    r = [a,b]
    return r

def solTtProCost(self):
    r = self.sol_TtProCost
    return r

def solTtTransCost(self):
    r = self.sol_TtTransCost
    return r

def solTtTardyCost(self):
    r = self.sol_TtTardyCost
    return r

def solTtRemainPro(self):
    r = self.sol_TtRemainPro
    return r

def solTtRemainTrans(self):
    r = self.sol_TtRemainTrans
    return r

def solSchedule(self):
    print('Produced Qty for first week ',self.sol_Pro1)
    print('Produced Qty for 3 weeks lookahead ',self.sol_Pro1)
    print('Delivery Qty for first week ',self.sol_Dlv1)
    print('Delivery Qty for 3 weeks lookahead ',self.sol_Dlv2)
    print('Delay Qty for first week ',self.sol_Dly1)
    print('Delay Qty for 3 weeks lookahead ', self.sol_Dly2)

def test(self):
    test_TtProCost = 0
    test_TtTransCost = 0
    test_TtTardyCost = 0
```

```
        test_TtRemainPro = 0
        test_TtRemainTrans = 0
        real_TtTardyCost = 0

        test_TtProCost_eachSc = [0] * len(dueDateSc)
        test_TtTransCost_eachSc = [0] * len(dueDateSc)
        test_TtTardyCost_eachSc = [0] * len(dueDateSc)
        test_TtRemainPro_eachSc = [0] * len(dueDateSc)
        test_TtRemainTrans_eachSc = [0] * len(dueDateSc)
        test_TtCost_eachSc = [0] * len(dueDateSc)
        real_TtTardyCost_eachSc = [0] * len(dueDateSc)
        real_TtCost_eachSc = [0] * len(dueDateSc)

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(0, 7):
                        if demandQty[k][j] != 0:
                            test_TtProCost = test_TtProCost + proCost[k][i] *
self.sol_Pro1.get((i, j, k, t), '')
                            test_TtTransCost = test_TtTransCost + transCost[k] * transDist[j][i]
* self.sol_Dlv1.get(
                                (i, j, k, t), '')

        for j in jobID:
            for k in partID:
                for t in range(0,7):
                    if demandQty[k][j] != 0:
                        test_TtTardyCost = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly1.get((j, k, t), '')

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(0, 7):
                        for s in scKey:
                            if demandQty[k][j] != 0:
                                test_TtProCost_eachSc[s] = test_TtProCost + proCost[k][i] *
self.sol_Pro1.get((i, j, k, t),

'')
                                test_TtTransCost_eachSc[s] = test_TtTransCost + transCost[k] *
transDist[j][
                                    i] * self.sol_Dlv1.get((i, j, k, t), '')
        for j in jobID:
            for k in partID:
                for t in range(0,7):
                    for s in scKey:
                        if demandQty[k][j] != 0:
                            test_TtTardyCost_eachSc[s] = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly1.get((j, k, t), '')
                            if t >= dueDate[k][j]:
                                if demandQty[k][j] > self.sol_TotalDlv1.get((j, k, t), ''):
                                    real_TtTardyCost_eachSc[s] = test_TtTardyCost +
delayCost[k][j]*(demandQty[k][j]-self.sol_TotalDlv1.get((j, k, t), ''))

        for i in shopID:
            for j in jobID:
                for k in partID:
                    for t in range(7, T):
                        for s in scKey:
                            if demandQty[k][j] != 0:
                                test_TtProCost = test_TtProCost + proCost[k][i] *
self.sol_Pro2.get((s, i, j, k, t), '') * \
                                                 self.prob[s]
                                test_TtTransCost = test_TtTransCost + transCost[k] *
transDist[j][i] * self.sol_Dlv2.get(
                                    (s, i, j, k, t), '') * self.prob[s]

                                test_TtProCost_eachSc[s] = test_TtProCost_eachSc[s] +
proCost[k][i] * self.sol_Pro2.get(
```

```
                                    (s, i, j, k, t), '')
                                test_TtTransCost_eachSc[s] = test_TtTransCost_eachSc[s] +
transCost[k] * transDist[j][
                                    i] * self.sol_Dlv2.get((s, i, j, k, t), '')

        for j in jobID:
            for k in partID:
                for t in range(7,T):
                    for s in scKey:
                        if demandQty[k][j] != 0:
                            test_TtTardyCost = test_TtTardyCost + delayCost[k][j] *
self.sol_Dly2.get((s, j, k, t),'') * self.prob[s]
                            test_TtTardyCost_eachSc[s] = test_TtTardyCost_eachSc[s] +
delayCost[k][j] * self.sol_Dly2.get((s, j, k, t), '')
                            if t >= dueDateSc[s][k][j]:
                                if demandQty[k][j] > self.sol_TotalDlv2.get((s,j, k, t), ''):
                                    #################### REMEMBER TO CHANGE SCENARIO FOR
self.sol_TotalDlv2.get((0,j, k, t), '')) FROM 0 TO 1 OR 2 OR 3 DEPENDING ON THE CONSIDERED
SCENARIO
                                    real_TtTardyCost_eachSc[s] = real_TtTardyCost_eachSc[s] +
delayCost[k][j]*(demandQty[k][j]-self.sol_TotalDlv2.get((0,j, k, t), ''))

        for j in jobID:
            for k in partID:
                for s in scKey:
                    test_TtRemainPro = test_TtRemainPro + proCostMax[k] * self.sol_Dly2.get((s,
j, k, T - 1), '') * self.prob[s]
                    test_TtRemainTrans = test_TtRemainTrans + transCostMax[k] * transDistMax[j] *
self.sol_Dly2.get(
                        (s, j, k, T - 1), '') * self.prob[s]

                    test_TtRemainPro_eachSc[s] = test_TtRemainPro + proCostMax[k] *
self.sol_Dly2.get((s, j, k, T - 1), '')
                    test_TtRemainTrans_eachSc[s] = test_TtRemainTrans + transCostMax[k] *
transDistMax[
                        j] * self.sol_Dly2.get((s, j, k, T - 1), '')

        for s in scKey:
            test_TtCost_eachSc[s] = round(
                test_TtProCost_eachSc[s] + test_TtTransCost_eachSc[s] +
test_TtTardyCost_eachSc[s] +
                test_TtRemainPro_eachSc[s] + test_TtRemainTrans_eachSc[s], 2)
            real_TtCost_eachSc[s] = round(
                self.sol_TtProCost + self.sol_TtTransCost + real_TtTardyCost_eachSc[s] +
                self.sol_TtRemainPro + self.sol_TtRemainTrans, 2)

        print('sol vs Test TtProCost ', self.sol_TtProCost, round(test_TtProCost, 2))
        print('sol vs Test TtTransCost ', self.sol_TtTransCost, round(test_TtTransCost, 2))
        print('sol vs Test TtTardyCost ', self.sol_TtTardyCost, round(test_TtTardyCost, 2))
        print('sol vs Test TtRemainPro ', self.sol_TtRemainPro, round(test_TtRemainPro, 2))
        print('sol vs Test TtRemainTrans ', self.sol_TtRemainTrans, round(test_TtRemainTrans, 2))
        print('TotalCost_allScenarios vs TotalCost_eachScenario ', round(self.sol_TtCost, 2),
test_TtCost_eachSc)
        print('TotalCost_allScenarios vs TotalCost_REAL ', round(self.sol_TtCost, 2),
real_TtCost_eachSc)
        print('Total REAL Tardy Cost each Scenario ', real_TtTardyCost_eachSc)
```

File sp_table_Trans_allSc.py

```
import sys
import xlwt
from PyQt5.QtWidgets import QMainWindow, QApplication, QWidget, QAction, QTableWidget,
QTableWidgetItem, QVBoxLayout, QFileDialog
from PyQt5.QtGui import QIcon
from PyQt5.QtCore import pyqtSlot
from PyQt5 import QtGui
```

```
import sp_input as ip
import sp_optModel as opt

class App(QWidget):

    def __init__(self):
        super().__init__()
        self.title = 'Delivery Schedule All Scenarios'
        self.left = 50
        self.top = 50
        self.width = 1700
        self.height = 950
        self.initUI()

    def initUI(self):
        self.setWindowTitle(self.title)
        self.setGeometry(self.left, self.top, self.width, self.height)

        self.createTable()

        # Add box layout, add table to box layout and add box layout to widget
        self.layout = QVBoxLayout()
        self.layout.addWidget(self.tableWidget)
        self.setLayout(self.layout)

        # Show widget
        self.show()

    def createTable(self):
        # Create table
        lgSh = len(ip.shN)
        lgJ = len(ip.jN)
        lgP = len(ip.pN)
        T = 28
        lgSc = len(opt.scKey)
        rowC = 1 + lgP * lgJ * lgSh * lgSc
        colC = 4+T+5
        self.tableWidget = QTableWidget()
        self.tableWidget.setRowCount(rowC)
        self.tableWidget.setColumnCount(colC)
        self.tableWidget.setColumnWidth(0, 60)
        self.tableWidget.setColumnWidth(1, 60)
        self.tableWidget.setColumnWidth(2, 60)
        self.tableWidget.setColumnWidth(3, 80)
        for i in range(0,T):
            self.tableWidget.setColumnWidth(i+4,40)
        self.tableWidget.setColumnWidth(4+T, 70)
        self.tableWidget.setColumnWidth(4+T+1, 70)
        self.tableWidget.setColumnWidth(4+T+2, 70)
        self.tableWidget.setColumnWidth(4+T+3, 70)
        self.tableWidget.setColumnWidth(4+T+4, 70)
        for i in range(0,rowC):
            self.tableWidget.setRowHeight(i,17)

        self.tableWidget.setItem(0, 0, QTableWidgetItem("Shop"))
        self.tableWidget.setItem(0, 1, QTableWidgetItem("Job"))
        self.tableWidget.setItem(0, 2, QTableWidgetItem("Part"))
        self.tableWidget.setItem(0, 3, QTableWidgetItem("Scenario"))
        for i in range(4, 4+T):
            self.tableWidget.setItem(0, i, QTableWidgetItem('D ' + str(i-3)))
        self.tableWidget.setItem(0, 4+T, QTableWidgetItem("Sum delivered"))
        self.tableWidget.setItem(0, 4+T+1, QTableWidgetItem("Sum produced"))
        self.tableWidget.setItem(0, 4+T+2, QTableWidgetItem("Sum all shops"))
        self.tableWidget.setItem(0, 4+T+3, QTableWidgetItem("Demand qty"))
        self.tableWidget.setItem(0, 4+T+4, QTableWidgetItem("Due date"))

        m = 1
        prb1 = 0.4
        prb2 = 0.3
        prb3 = 0.1
        prb4 = 0.2
```

```
        OPT = opt.optModel(m, prb1, prb2, prb3, prb4)

        for s in range(0, lgSc):
            for i in range(0, lgSh):
                for j in range(0, lgJ):
                    for k in range(0, lgP):
                        pr = 0
                        dlv = 0
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + 1, 0,
QTableWidgetItem('Shop ' + str(i + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + 1, 1,
QTableWidgetItem('Job ' + str(j + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc * k
+ 1, 2, QTableWidgetItem('Part ' + str(k + 1)))
                        self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc * k
+ s + 1, 3, QTableWidgetItem('Sc ' + str(s + 1)))
                        if ip.jDmd[k][j * 3 + 1] != 0:
                            self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T +
3,
                                                     QTableWidgetItem(str(ip.jDmd[k][j * 3 + 1])))   #
Demand quantity
                        if opt.dueDateSc[s][k][j] != 0:
                            self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T +
4,
                                                     QTableWidgetItem(str(opt.dueDateSc[s][k][j]+1)))
# Due date
                        for t in range(0,7):
                            if OPT.sol_Dlv1.get((i,j,k,t),'') != 0:
                                self.tableWidget.setItem(i*lgSc*lgP*lgJ+lgSc*lgP*j+lgSc*k+s+1,
t+4, QTableWidgetItem(str(round(OPT.sol_Dlv1.get((i,j,k,t),'')))))
                                dlv = dlv+OPT.sol_Dlv1.get((i,j,k,t),'')
                            if OPT.sol_Pro1.get((i,j,k,t),'') != 0: #total produced quantity
                                pr = pr+OPT.sol_Pro1.get((i,j,k,t),'')
                        for t in range(7,T):
                            if OPT.sol_Dlv2.get((s,i,j,k,t),'') != 0:
                                self.tableWidget.setItem(i*lgSc*lgP*lgJ+lgSc*lgP*j+lgSc*k+s+1,
t+4, QTableWidgetItem(str(round(OPT.sol_Dlv2.get((s,i,j,k,t),'')))))
                                dlv = dlv+OPT.sol_Dlv2.get((s,i,j,k,t),'')
                            if OPT.sol_Pro2.get((s,i,j,k,t),'') != 0: #total produced quantity
                                pr = pr+OPT.sol_Pro2.get((s,i,j,k,t),'')

                        if dlv != 0:
                            self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc
* k + s + 1, 4 + T, QTableWidgetItem(str(round(dlv)))) #Total delivered quantity
                        if pr != 0:
                            self.tableWidget.setItem(i * lgSc * lgP * lgJ + lgSc * lgP * j + lgSc
* k + s + 1, 4 + T + 1, QTableWidgetItem(str(round(pr)))) #Total produced quantity
        for s in range(0, lgSc):
            for j in range(0, lgJ):
                for k in range(0,lgP):
                    A = 0
                    for t in range(0,7):
                        for i in range(0,lgSh):
                            A = A + OPT.sol_Dlv1.get((i,j,k,t),'')
                    for t in range(7,T):
                        for i in range(0,lgSh):
                            A = A + OPT.sol_Dlv2.get((s,i,j,k,t),'')
                    if A !=0:
                        self.tableWidget.setItem(lgSc * lgP * j + lgSc * k + s + 1, 4 + T + 2,
QTableWidgetItem(str(round(A)))) #Sum delivered quantity of all shops

        # table selection change
        self.tableWidget.doubleClicked.connect(self.on_click)

        # save data to a excel file
        filename = QFileDialog.getSaveFileName(self, 'Save File', '', ".xls(*.xls)")
        wbk = xlwt.Workbook()
        sheet = wbk.add_sheet('TransSch_allSc', cell_overwrite_ok=True)
        for i in range(0, rowC):
            for j in range(0, colC):
                if self.tableWidget.item(i,j) != None:
```

```
                    mycell = self.tableWidget.item(i,j).text()
                    sheet.write(i,j,mycell)
        wbk.save(filename[0])

    @pyqtSlot()
    def on_click(self):
        print("\n")
        for currentQTableWidgetItem in self.tableWidget.selectedItems():
            print(currentQTableWidgetItem.row(), currentQTableWidgetItem.column(),
currentQTableWidgetItem.text())


if __name__ == '__main__':
    app = QApplication(sys.argv)
    ex = App()
    sys.exit(app.exec_())
```

File sp_table_Prod_Single_Sc1.py

```
import sys
import xlwt
from PyQt5.QtWidgets import QMainWindow, QApplication, QWidget, QAction, QTableWidget,
QTableWidgetItem, QVBoxLayout, QFileDialog
from PyQt5.QtGui import QIcon
from PyQt5.QtCore import pyqtSlot
from PyQt5 import QtGui
import sp_input as ip
import sp_optModel_Single_Sc1 as opt

class App(QWidget):

    def __init__(self):
        super().__init__()
        self.title = 'Production Schedule Scenario 1'
        self.left = 50
        self.top = 50
        self.width = 1700
        self.height = 950
        self.initUI()

    def initUI(self):
        self.setWindowTitle(self.title)
        self.setGeometry(self.left, self.top, self.width, self.height)

        self.createTable()

        # Add box layout, add table to box layout and add box layout to widget
        self.layout = QVBoxLayout()
        self.layout.addWidget(self.tableWidget)
        self.setLayout(self.layout)

        # Show widget
        self.show()

    def createTable(self):
        # Create table
        lgSh = len(ip.shN)
        lgJ = len(ip.jN)
        lgP = len(ip.pN)
        T = 28
        lgSc = len(opt.scKey)
        rowC = 1 + lgP * lgJ * lgSh
        colC = 3+T+5
        self.tableWidget = QTableWidget()
        self.tableWidget.setRowCount(rowC)
        self.tableWidget.setColumnCount(colC)
        self.tableWidget.setColumnWidth(0, 60)
        self.tableWidget.setColumnWidth(1, 60)
```

```
        self.tableWidget.setColumnWidth(2, 60)
        for i in range(0,T):
            self.tableWidget.setColumnWidth(i+3,40)
        self.tableWidget.setColumnWidth(3+T, 70)
        self.tableWidget.setColumnWidth(3+T+1, 70)
        self.tableWidget.setColumnWidth(3+T+2, 70)
        self.tableWidget.setColumnWidth(3+T+3, 70)
        self.tableWidget.setColumnWidth(3+T+4, 70)
        for i in range(0,rowC):
            self.tableWidget.setRowHeight(i,17)

        self.tableWidget.setItem(0, 0, QTableWidgetItem("Shop"))
        self.tableWidget.setItem(0, 1, QTableWidgetItem("Job"))
        self.tableWidget.setItem(0, 2, QTableWidgetItem("Part"))
        for i in range(3, 3+T):
            self.tableWidget.setItem(0, i, QTableWidgetItem('D ' + str(i-2)))
        self.tableWidget.setItem(0, 3+T, QTableWidgetItem("Sum produced"))
        self.tableWidget.setItem(0, 3+T+1, QTableWidgetItem("Sum delivered"))
        self.tableWidget.setItem(0, 3+T+2, QTableWidgetItem("Sum all shops"))
        self.tableWidget.setItem(0, 3+T+3, QTableWidgetItem("Demand qty"))
        self.tableWidget.setItem(0, 3+T+4, QTableWidgetItem("Due date"))

        m = 1
        prb1 = 1
        prb2 = 0
        prb3 = 0
        prb4 = 0
        OPT = opt.optModel(m, prb1, prb2, prb3, prb4)

        for i in range (0, lgSh):
            for j in range(0, lgJ):
                for k in range(0, lgP):
                    pr = 0
                    dlv = 0
                    self.tableWidget.setItem(i * lgP * lgJ + 1, 0, QTableWidgetItem('Shop ' +
str(i + 1)))
                    self.tableWidget.setItem(i * lgP * lgJ + lgP * j + 1, 1,
QTableWidgetItem('Job ' + str(j + 1)))
                    self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 2,
QTableWidgetItem('Part ' + str(k + 1)))
                    if ip.jDmd[k][j * 3 + 1] != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 3,
                                                 QTableWidgetItem(str(ip.jDmd[k][j * 3 + 1])))   #
Demand quantity
                    if opt.dueDateSc[0][k][j] != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 4,
                                                 QTableWidgetItem(str(opt.dueDateSc[0][k][j]+1)))
# Due date
                    for t in range(0,7):
                        if OPT.sol_Pro1.get((i,j,k,t),'') != 0:
                            self.tableWidget.setItem(i*lgP*lgJ+lgP*j+k+1, t+3,
QTableWidgetItem(str(round(OPT.sol_Pro1.get((i,j,k,t),'')))))
                            pr = pr+OPT.sol_Pro1.get((i,j,k,t),'')
                        if OPT.sol_Dlv1.get((i,j,k,t),'') != 0: #total delivered quantity
                            dlv = dlv+OPT.sol_Dlv1.get((i,j,k,t),'')
                    for t in range(7,T):
                        if OPT.sol_Pro2.get((0,i,j,k,t),'') != 0:
                            self.tableWidget.setItem(i*lgP*lgJ+lgP*j+k+1, t+3,
QTableWidgetItem(str(round(OPT.sol_Pro2.get((0,i,j,k,t),'')))))
                            pr = pr+OPT.sol_Pro2.get((0,i,j,k,t),'')
                        if OPT.sol_Dlv2.get((0,i,j,k,t),'') != 0: #total delivered quantity
                            dlv = dlv+OPT.sol_Dlv2.get((0,i,j,k,t),'')

                    if pr != 0:
                        self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 3 + T,
QTableWidgetItem(str(round(pr)))) #Total production quantity
                    if dlv != 0:
                        self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 3 + T + 1,
QTableWidgetItem(str(round(dlv)))) #Total deliver quantity
        for j in range(0, lgJ):
            for k in range(0,lgP):
```

```
                A = 0
                for t in range(0,7):
                    for i in range(0,lgSh):
                        A = A + OPT.sol_Pro1.get((i,j,k,t),'')
                for t in range(7,T):
                    for i in range(0,lgSh):
                        A = A + OPT.sol_Pro2.get((0,i,j,k,t),'')
                if A !=0:
                    self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 2,
QTableWidgetItem(str(round(A)))) #Sum production quantity of all shops

        # table selection change
        self.tableWidget.doubleClicked.connect(self.on_click)

        # save data to a excel file
        filename = QFileDialog.getSaveFileName(self, 'Save File', '', ".xls(*.xls)")
        wbk = xlwt.Workbook()
        sheet = wbk.add_sheet('ProdSch', cell_overwrite_ok=True)
        for i in range(0, rowC):
            for j in range(0, colC):
                if self.tableWidget.item(i,j) != None:
                    mycell = self.tableWidget.item(i,j).text()
                    sheet.write(i,j,mycell)
        wbk.save(filename[0])

    @pyqtSlot()
    def on_click(self):
        print("\n")
        for currentQTableWidgetItem in self.tableWidget.selectedItems():
            print(currentQTableWidgetItem.row(), currentQTableWidgetItem.column(),
currentQTableWidgetItem.text())


if __name__ == '__main__':
    app = QApplication(sys.argv)
    ex = App()
    sys.exit(app.exec_())
```

File sp_table_Trans_Single_Sc1.py

```
import sys
import xlwt
from PyQt5.QtWidgets import QMainWindow, QApplication, QWidget, QAction, QTableWidget,
QTableWidgetItem, QVBoxLayout, QFileDialog
from PyQt5.QtGui import QIcon
from PyQt5.QtCore import pyqtSlot
from PyQt5 import QtGui
import sp_input as ip
import sp_optModel_Single_Sc1 as opt

class App(QWidget):

    def __init__(self):
        super().__init__()
        self.title = 'Transportation Schedule Scenario 1'
        self.left = 50
        self.top = 50
        self.width = 1700
        self.height = 950
        self.initUI()

    def initUI(self):
        self.setWindowTitle(self.title)
        self.setGeometry(self.left, self.top, self.width, self.height)

        self.createTable()

        # Add box layout, add table to box layout and add box layout to widget
```

```
        self.layout = QVBoxLayout()
        self.layout.addWidget(self.tableWidget)
        self.setLayout(self.layout)

        # Show widget
        self.show()

    def createTable(self):
        # Create table
        lgSh = len(ip.shN)
        lgJ = len(ip.jN)
        lgP = len(ip.pN)
        T = 28
        lgSc = len(opt.scKey)
        rowC = 1 + lgP * lgJ * lgSh
        colC = 3+T+5
        self.tableWidget = QTableWidget()
        self.tableWidget.setRowCount(rowC)
        self.tableWidget.setColumnCount(colC)
        self.tableWidget.setColumnWidth(0, 60)
        self.tableWidget.setColumnWidth(1, 60)
        self.tableWidget.setColumnWidth(2, 60)
        for i in range(0,T):
            self.tableWidget.setColumnWidth(i+3,40)
        self.tableWidget.setColumnWidth(3+T, 70)
        self.tableWidget.setColumnWidth(3+T+1, 75)
        self.tableWidget.setColumnWidth(3+T+2, 70)
        self.tableWidget.setColumnWidth(3+T+3, 70)
        self.tableWidget.setColumnWidth(3+T+4, 70)
        for i in range(0,rowC):
            self.tableWidget.setRowHeight(i,17)

        self.tableWidget.setItem(0, 0, QTableWidgetItem("Shop"))
        self.tableWidget.setItem(0, 1, QTableWidgetItem("Job"))
        self.tableWidget.setItem(0, 2, QTableWidgetItem("Part"))
        for i in range(3, 3+T):
            self.tableWidget.setItem(0, i, QTableWidgetItem('D ' + str(i-2)))
        self.tableWidget.setItem(0, 3+T, QTableWidgetItem("Sum delivered"))
        self.tableWidget.setItem(0, 3+T+1, QTableWidgetItem("Sum produced"))
        self.tableWidget.setItem(0, 3+T+2, QTableWidgetItem("Sum all shops"))
        self.tableWidget.setItem(0, 3+T+3, QTableWidgetItem("Demand qty"))
        self.tableWidget.setItem(0, 3+T+4, QTableWidgetItem("Due date"))

        m = 1
        prb1 = 1
        prb2 = 0
        prb3 = 0
        prb4 = 0
        OPT = opt.optModel(m,prb1,prb2,prb3,prb4)

        for i in range(0, lgSh):
            for j in range(0, lgJ):
                for k in range(0, lgP):
                    pr = 0
                    dlv = 0
                    self.tableWidget.setItem(i * lgP * lgJ + 1, 0, QTableWidgetItem('Shop ' +
str(i + 1)))
                    self.tableWidget.setItem(i * lgP * lgJ + lgP * j + 1, 1,
QTableWidgetItem('Job ' + str(j + 1)))
                    self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 2,
QTableWidgetItem('Part ' + str(k + 1)))
                    if ip.jDmd[k][j * 3 + 1] != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 3,
                                                 QTableWidgetItem(str(ip.jDmd[k][j * 3 + 1])))   #
Demand quantity
                    if opt.dueDateSc[0][k][j] != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 4,
                                                 QTableWidgetItem(str(opt.dueDateSc[0][k][j]+1)))
# Due date
                    for t in range(0,7):
                        if OPT.sol_Dlv1.get((i,j,k,t),'') != 0:
```

```
                            self.tableWidget.setItem(i*lgP*lgJ+lgP*j+k+1, t+3,
QTableWidgetItem(str(round(OPT.sol_Dlv1.get((i,j,k,t),'')))))
                            dlv = dlv+OPT.sol_Dlv1.get((i,j,k,t),'')
                        if OPT.sol_Pro1.get((i,j,k,t),'') != 0: #total produced quantity
                            pr = pr+OPT.sol_Pro1.get((i,j,k,t),'')
                    for t in range(7,T):
                        if OPT.sol_Dlv2.get((0,i,j,k,t),'') != 0:
                            self.tableWidget.setItem(i*lgP*lgJ+lgP*j+k+1, t+3,
QTableWidgetItem(str(round(OPT.sol_Dlv2.get((0,i,j,k,t),'')))))
                            dlv = dlv+OPT.sol_Dlv2.get((0,i,j,k,t),'')
                        if OPT.sol_Pro2.get((0,i,j,k,t),'') != 0: #total produced quantity
                            pr = pr+OPT.sol_Pro2.get((0,i,j,k,t),'')

                    if dlv != 0:
                        self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 3 + T,
QTableWidgetItem(str(round(dlv)))) #Total delivered quantity
                    if pr != 0:
                        self.tableWidget.setItem(i * lgP * lgJ + lgP * j + k + 1, 3 + T + 1,
QTableWidgetItem(str(round(pr)))) #Total produced quantity
        for j in range(0, lgJ):
            for k in range(0,lgP):
                A = 0
                for t in range(0,7):
                    for i in range(0,lgSh):
                        A = A + OPT.sol_Pro1.get((i,j,k,t),'')
                for t in range(7,T):
                    for i in range(0,lgSh):
                        A = A + OPT.sol_Pro2.get((0,i,j,k,t),'')
                if A !=0:
                    self.tableWidget.setItem(lgP * j + k + 1, 3 + T + 2,
QTableWidgetItem(str(round(A)))) #Sum production quantity of all shops

        # table selection change
        self.tableWidget.doubleClicked.connect(self.on_click)

        # save data to a excel file
        filename = QFileDialog.getSaveFileName(self, 'Save File', '', ".xls(*.xls)")
        wbk = xlwt.Workbook()
        sheet = wbk.add_sheet('TransSch', cell_overwrite_ok=True)
        for i in range(0, rowC):
            for j in range(0, colC):
                if self.tableWidget.item(i,j) != None:
                    mycell = self.tableWidget.item(i,j).text()
                    sheet.write(i,j,mycell)
        wbk.save(filename[0])

    @pyqtSlot()
    def on_click(self):
        print("\n")
        for currentQTableWidgetItem in self.tableWidget.selectedItems():
            print(currentQTableWidgetItem.row(), currentQTableWidgetItem.column(),
currentQTableWidgetItem.text())


if __name__ == '__main__':
    app = QApplication(sys.argv)
    ex = App()
    sys.exit(app.exec_())
```

File sp_table_Tardy_Single_Sc1.py

```
import sys
import xlwt
from PyQt5.QtWidgets import QMainWindow, QApplication, QWidget, QAction, QTableWidget,
QTableWidgetItem, QVBoxLayout, QFileDialog
from PyQt5.QtGui import QIcon
from PyQt5.QtCore import pyqtSlot
import sp_input as ip
```

```
import sp_optModel_Single_Sc1 as opt

class App(QWidget):

    def __init__(self):
        super().__init__()
        self.title = 'Tardiness Quantity at Scenario 1'
        self.left = 50
        self.top = 50
        self.width = 1400
        self.height = 600
        self.initUI()

    def initUI(self):
        self.setWindowTitle(self.title)
        self.setGeometry(self.left, self.top, self.width, self.height)

        self.createTable()

        # Add box layout, add table to box layout and add box layout to widget
        self.layout = QVBoxLayout()
        self.layout.addWidget(self.tableWidget)
        self.setLayout(self.layout)

        # Show widget
        self.show()

    def createTable(self):
        # Create table
        T = 28
        lgSh = len(ip.shN)
        lgJ = len(ip.jN)
        lgP = len(ip.pN)
        rowC = 1 + lgP * lgJ
        colC = 2+T
        self.tableWidget = QTableWidget()
        self.tableWidget.setRowCount(rowC)
        self.tableWidget.setColumnCount(colC)
        self.tableWidget.setColumnWidth(0, 60)
        self.tableWidget.setColumnWidth(1, 60)
        for i in range(0,T):
            self.tableWidget.setColumnWidth(i+2,40)
        for i in range(0,rowC):
            self.tableWidget.setRowHeight(i,17)
        self.tableWidget.setItem(0, 0, QTableWidgetItem("Job"))
        self.tableWidget.setItem(0, 1, QTableWidgetItem("Part"))
        for i in range(2, 2+T):
            self.tableWidget.setItem(0, i, QTableWidgetItem('D ' + str(i-1)))

        m = 1
        prb1 = 1
        prb2 = 0
        prb3 = 0
        prb4 = 0
        OPT = opt.optModel(m, prb1, prb2, prb3, prb4)

        for j in range(0, lgJ):
            for k in range(0,lgP):
                self.tableWidget.setItem(lgP * j + 1, 0, QTableWidgetItem('Job ' + str(j + 1)))
                self.tableWidget.setItem(lgP * j + k + 1, 1, QTableWidgetItem('Part ' + str(k + 
1)))
                for t in range(0,7):
                    if OPT.sol_Dly1.get((j,k,t),'') != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, t+2, 
QTableWidgetItem(str(round(OPT.sol_Dly1.get((0,j,k,t),'')))))
                for t in range(7,T):
                    if OPT.sol_Dly2.get((0,j,k,t),'') != 0:
                        self.tableWidget.setItem(lgP * j + k + 1, t+2, 
QTableWidgetItem(str(round(OPT.sol_Dly2.get((0,j,k,t),'')))))

        # table selection change
```

```
        self.tableWidget.doubleClicked.connect(self.on_click)

        # save data to a excel file
        filename = QFileDialog.getSaveFileName(self, 'Save File', '', ".xls(*.xls)")
        wbk = xlwt.Workbook()
        sheet = wbk.add_sheet('TardySch', cell_overwrite_ok=True)
        for i in range(0, rowC):
            for j in range(0, colC):
                if self.tableWidget.item(i,j) != None:
                    mycell = self.tableWidget.item(i,j).text()
                    sheet.write(i,j,mycell)
        wbk.save(filename[0])

    @pyqtSlot()
    def on_click(self):
        print("\n")
        for currentQTableWidgetItem in self.tableWidget.selectedItems():
            print(currentQTableWidgetItem.row(), currentQTableWidgetItem.column(),
currentQTableWidgetItem.text())


if __name__ == '__main__':
    app = QApplication(sys.argv)
    ex = App()
    sys.exit(app.exec_())
```

File sp_graph.py

```
import os
import sp_optModel as opt
import sp_optModel_Single_Sc1 as opt1
import sp_optModel_Single_Sc2 as opt2
import sp_optModel_Single_Sc3 as opt3
import sp_optModel_Single_Sc4 as opt4
import matplotlib.pyplot as plt
from matplotlib.backends.backend_pdf import PdfPages
from matplotlib.patches import Ellipse, Polygon
import numpy as np
import math

class Pareto(object):
    def __init__(self, stepQty=''):
        self.stepQty = stepQty
        pr1 = 0.4
        pr2 = 0.3
        pr3 = 0.1
        pr4 = 0.2

        self.lst_TtCost = [0]*(self.stepQty+1)
        self.lst_TtDelay = [0]*(self.stepQty+1)
        self.lst0_TtCost = [0]*(self.stepQty+1)
        self.lst0_TtDelay = [0]*(self.stepQty+1)
        self.lst1_TtCost = [0]*(self.stepQty+1)
        self.lst1_TtDelay = [0]*(self.stepQty+1)
        self.lst2_TtCost = [0]*(self.stepQty+1)
        self.lst2_TtDelay = [0]*(self.stepQty+1)
        self.lst3_TtCost = [0]*(self.stepQty+1)
        self.lst3_TtDelay = [0]*(self.stepQty+1)
        self.lst4_TtCost = [0]*(self.stepQty+1)
        self.lst4_TtDelay = [0]*(self.stepQty+1)

        self.lst_TtCost_TtDelay = [0]*(self.stepQty+1)
        step = 1/self.stepQty
        c = 0
        for i in range(0,self.stepQty+1):
            c = c + i*step
            OPT = opt.optModel(c, pr1, pr2, pr3, pr4)
            OPT1 = opt1.optModel(c, 1, 0, 0, 0)
```

```
            OPT2 = opt2.optModel(c, 1, 0, 0, 0)
            OPT3 = opt3.optModel(c, 1, 0, 0, 0)
            OPT4 = opt4.optModel(c, 1, 0, 0, 0)

            self.lst_TtCost[i] = OPT.solTtCost()
            self.lst_TtDelay[i] = OPT.solTtDelay()
            self.lst_TtCost_TtDelay[i] = OPT.solTtCost_TtDelay()
            self.lst1_TtCost[i] = OPT1.solTtCost()
            self.lst1_TtDelay[i] = OPT1.solTtDelay()
            self.lst2_TtCost[i] = OPT2.solTtCost()
            self.lst2_TtDelay[i] = OPT2.solTtDelay()
            self.lst3_TtCost[i] = OPT3.solTtCost()
            self.lst3_TtDelay[i] = OPT3.solTtDelay()
            self.lst4_TtCost[i] = OPT4.solTtCost()
            self.lst4_TtDelay[i] = OPT4.solTtDelay()


    def lstTtCost(self):
        lst = self.lst_TtCost
        print('Total Cost')
        for i in lst:
            print(i)
        return lst

    def lstTtDelay(self):
        lst = self.lst_TtDelay
        print('Total Delay')
        for i in lst:
            print(i)
        return lst

    def lstTtCost_TtDelay(self):
        lst = self.lst_TtCost_TtDelay
        return lst

    def lst1TtCost(self):
        lst = self.lst1_TtCost
        print('Total Cost Sc1')
        for i in lst:
            print(i)
        return lst

    def lst1TtDelay(self):
        lst = self.lst1_TtDelay
        print('Total Delay Sc1')
        for i in lst:
            print(i)
        return lst

    def lst2TtCost(self):
        lst = self.lst2_TtCost
        print('Total Cost Sc2')
        for i in lst:
            print(i)
        return lst

    def lst2TtDelay(self):
        lst = self.lst2_TtDelay
        print('Total Delay Sc2')
        for i in lst:
            print(i)
        return lst

    def lst3TtCost(self):
        lst = self.lst3_TtCost
        print('Total Cost Sc3')
        for i in lst:
            print(i)
        return lst

    def lst3TtDelay(self):
```

```
        lst = self.lst3_TtDelay
        print('Total Delay Sc3')
        for i in lst:
            print(i)
        return lst

    def lst4TtCost(self):
        lst = self.lst4_TtCost
        print('Total Cost Sc4')
        for i in lst:
            print(i)
        return lst

    def lst4TtDelay(self):
        lst = self.lst4_TtDelay
        print('Total Delay Sc4')
        for i in lst:
            print(i)
        return lst

    def grPareto_average(self):
        graph0 = plt.plot(self.lstTtDelay(),self.lstTtCost())
        plt.setp(graph0, marker ='o', markersize = 5, markerfacecolor = 'red')
        plt.title('Pareto Chart')
        plt.xlabel('Total Delay (unit-day)')
        plt.ylabel('Total Cost ($)')
        plt.grid(True)
        plt.show()

    def grPareto_all(self):
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)

        graph = plt.plot(self.lstTtDelay(),self.lstTtCost(),'ro-',label = 'SP with 4 Scenarios')
        graph1 = plt.plot(self.lst1TtDelay(),self.lst1TtCost(),'gv-',label = 'Scenario 1')
        graph2 = plt.plot(self.lst2TtDelay(), self.lst2TtCost(),'b*-',label = 'Scenario 2')
        graph3 = plt.plot(self.lst3TtDelay(), self.lst3TtCost(),'yx-',label = 'Scenario 3')
        graph4 = plt.plot(self.lst4TtDelay(), self.lst4TtCost(),'cs-',label = 'Scenario 4')


        plt.setp(graph, marker ='o', markersize = 8, markerfacecolor = 'red')
        plt.setp(graph1, marker='v', markersize=8, markerfacecolor='green')
        plt.setp(graph2, marker='*', markersize=8, markerfacecolor='blue')
        plt.setp(graph3, marker='x', markersize=8, markerfacecolor='yellow')
        plt.setp(graph4, marker='s', markersize=8, markerfacecolor='cyan')

        plt.legend(['SP Model with 4 Scenarios', 'Scenario 1', 'Scenario 2', 'Scenario 3',
'Scenario 4'], loc=8, ncol=3, bbox_to_anchor=(0.5, -0.3))
        #plt.legend(handles=[graph0, graph1, graph2, graph3, graph4])

        plt.title('Pareto Chart')
        plt.xlabel('Total Delay (unit-day)')
        plt.ylabel('Total Cost ($)')
        plt.grid(True)
        plt.show()

class SpScenarios(object):
    ###### Generate graph for the case with SP program with all scenario weighted and the case
with SP program but single scenario
    def __init__(self, m=''):
        self.m = m
        self.OPT0 = opt.optModel(self.m,0.4,0.3,0.1,0.2)
        self.OPT1 = opt1.optModel(self.m,1,0,0,0)
        self.OPT2 = opt2.optModel(self.m,1,0,0,0)
        self.OPT3 = opt3.optModel(self.m,1,0,0,0)
        self.OPT4 = opt4.optModel(self.m,1,0,0,0)
    def TtCost_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtCost()
        lst[1] = self.OPT1.solTtCost()
        lst[2] = self.OPT2.solTtCost()
```

```
        lst[3] = self.OPT3.solTtCost()
        lst[4] = self.OPT4.solTtCost()
        return lst
    def TtPrCost_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtProCost()
        lst[1] = self.OPT1.solTtProCost()
        lst[2] = self.OPT2.solTtProCost()
        lst[3] = self.OPT3.solTtProCost()
        lst[4] = self.OPT4.solTtProCost()
        return lst
    def TtTransCost_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtTransCost()
        lst[1] = self.OPT1.solTtTransCost()
        lst[2] = self.OPT2.solTtTransCost()
        lst[3] = self.OPT3.solTtTransCost()
        lst[4] = self.OPT4.solTtTransCost()
        return lst
    def TtTardyCost_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtTardyCost()
        lst[1] = self.OPT1.solTtTardyCost()
        lst[2] = self.OPT2.solTtTardyCost()
        lst[3] = self.OPT3.solTtTardyCost()
        lst[4] = self.OPT4.solTtTardyCost()
        return lst
    def TtRemainProd_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtRemainPro()
        lst[1] = self.OPT1.solTtRemainPro()
        lst[2] = self.OPT2.solTtRemainPro()
        lst[3] = self.OPT3.solTtRemainPro()
        lst[4] = self.OPT4.solTtRemainPro()
        return lst
    def TtRemainTrans_eachSc(self):
        lst = [0]*5
        lst[0] = self.OPT0.solTtRemainTrans()
        lst[1] = self.OPT1.solTtRemainTrans()
        lst[2] = self.OPT2.solTtRemainTrans()
        lst[3] = self.OPT3.solTtRemainTrans()
        lst[4] = self.OPT4.solTtRemainTrans()
        return lst

    def HandlingCost(self):
        lst = [0]*5
        lst[1] = self.OPT1.handlingCost()
        lst[2] = self.OPT2.handlingCost()
        lst[3] = self.OPT3.handlingCost()
        lst[4] = self.OPT4.handlingCost()
        lst[0] = math.trunc(0.4*lst[1] + 0.3*lst[2] + 0.1*lst[3] + 0.2*lst[4])
        return lst

    def TtCost_eachSc_woHandling(self):
        a = self.TtCost_eachSc()
        lst = [a[0], a[1],a[2],a[3],a[4]]
        return lst

    def TtCost_eachSc_withHandling(self):
        lst1 = self.TtCost_eachSc_woHandling()
        lst2 = self.HandlingCost()
        lst = [0]*5
        lst[0] = lst1[0]+lst2[0]
        lst[1] = lst1[1]+lst2[1]
        lst[2] = lst1[2]+lst2[2]
        lst[3] = lst1[3]+lst2[3]
        lst[4] = lst1[4]+lst2[4]
        return lst

    def SpCostGraph(self):
        name = ['Total Cost','Production Cost','Transportation Cost','Delay Cost','Remaining Qty
```

```
Production Cost', 'Remaining Qty Transportation Cost']
        ScName = ['SP Model with 4 Scenarios','Single Scenario with SC 1','Single Scenario with
SC 2', 'Single Scenario with SC 3', 'Single Scenario with SC 4']
        SC = np.array([1.5, 3.0, 4.5, 6.0, 7.5])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)
        ax = plt.subplot(111)
        ax.bar(SC-0.15, self.TtCost_eachSc(), width=0.15, color='darkorange', align='center',
hatch="\\", edgecolor="r" )
        for i in range(0,5):
            ax.text(SC[i]-0.15-0.075, self.TtCost_eachSc()[i]+30000,
str(self.TtCost_eachSc()[i]),color='k')

        ax.bar(SC, self.TtPrCost_eachSc(), width=0.15, color='lightgray', align='center',
hatch="*", edgecolor="g")
        for i in range(0,5):
            ax.text(SC[i]-0.075, self.TtPrCost_eachSc()[i]+30000,
str(self.TtPrCost_eachSc()[i]),color='k')

        ax.bar(SC+0.15, self.TtTransCost_eachSc(), width=0.15, color='c', align='center',
hatch="/", edgecolor="greenyellow")
        for i in range(0,5):
            ax.text(SC[i]+0.15-0.075, self.TtTransCost_eachSc()[i]+270000,
str(self.TtTransCost_eachSc()[i]),color='k')

        ax.bar(SC+0.3, self.TtTardyCost_eachSc(), width=0.15, color='aquamarine', align='center',
hatch=".", edgecolor="b")
        for i in range(0,5):
            ax.text(SC[i]+0.3-0.075, self.TtTardyCost_eachSc()[i]+110000,
str(self.TtTardyCost_eachSc()[i]),color='k')

        ax.bar(SC+0.45, self.TtRemainProd_eachSc(), width=0.15, color='thistle', align='center',
hatch="o", edgecolor="m")
        for i in range(0,5):
            ax.text(SC[i]+0.45-0.075, self.TtRemainProd_eachSc()[i]+30000,
str(self.TtRemainProd_eachSc()[i]),color='k')

        ax.bar(SC+0.6, self.TtRemainTrans_eachSc(), width=0.15, color='none', align='center',
edgecolor="k")
        for i in range(0,5):
            ax.text(SC[i]+0.6-0.075, self.TtRemainTrans_eachSc()[i]+50,
str(self.TtRemainTrans_eachSc()[i]),color='k')


        #graph = plt.plot(SC, self.TtCost_eachSc(), 'r--', SC, self.TtPrCost_eachSc(), 'bs', SC,
self.TtTransCost_eachSc(), 'g^', SC, self.TtTardyCost_eachSc(), 'rs')
        #plt.setp(graph, markersize = 5)
        #plt.setp(graph, markerfacecolor = 'C0')

        plt.title('Total Costs($) at Various Scenarios')
        #plt.xlabel('Scenario')
        #plt.ylabel('Total Cost ($)')
        plt.xticks(SC, ScName)

        legend = plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.25), ncol=3, markerscale = 3000)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtCostPartsScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpCostGraph_allScWeig(self):
        name = ['Total Cost','Production Cost','Transportation Cost','Delay Cost','Remaining Qty
Production Cost', 'Remaining Qty Transportation Cost']
        ScName = ['SP Model with all Scenarios']
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)
        ax = plt.subplot(111)
        ax.bar(1-0.15, self.TtCost_eachSc()[0], width=0.15, color='darkorange', align='center',
hatch="\\", edgecolor="r" )
        ax.text(1-0.15-0.075, self.TtCost_eachSc()[0]+30000,
```

```
str(self.TtCost_eachSc()[0]),color='k')

        ax.bar(1, self.TtPrCost_eachSc()[0], width=0.15, color='lightgray', align='center',
hatch="*", edgecolor="g")
        ax.text(1-0.075, self.TtPrCost_eachSc()[0]+30000,
str(self.TtPrCost_eachSc()[0]),color='k')

        ax.bar(1+0.15, self.TtTransCost_eachSc()[0], width=0.15, color='c', align='center',
hatch="/", edgecolor="greenyellow")
        ax.text(1+0.15-0.075, self.TtTransCost_eachSc()[0]+270000,
str(self.TtTransCost_eachSc()[0]),color='k')

        ax.bar(1+0.3, self.TtTardyCost_eachSc()[0], width=0.15, color='aquamarine',
align='center', hatch=".", edgecolor="b")
        ax.text(1+0.3-0.075, self.TtTardyCost_eachSc()[0]+110000,
str(self.TtTardyCost_eachSc()[0]),color='k')

        ax.bar(1+0.45, self.TtRemainProd_eachSc()[0], width=0.15, color='thistle',
align='center', hatch="o", edgecolor="m")
        ax.text(1+0.45-0.075, self.TtRemainProd_eachSc()[0]+30000,
str(self.TtRemainProd_eachSc()[0]),color='k')

        ax.bar(1+0.6, self.TtRemainTrans_eachSc()[0], width=0.15, color='none', align='center',
edgecolor="k")
        ax.text(1+0.6-0.075, self.TtRemainTrans_eachSc()[0]+50,
str(self.TtRemainTrans_eachSc()[0]),color='k')

        plt.title('Total Cost($) of the Case with all Scenarios Weighted')
        #plt.xticks(SC, ScName)

        legend = plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.25), ncol=3, markerscale = 3000)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtCostAllScWeighted.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpCostGraph_singleSc_Sc1(self):
        name = ['Total Cost','Production Cost','Transportation Cost','Delay Cost','Remaining Qty
Production Cost', 'Remaining Qty Transportation Cost']
        ScName = ['Single Scenario with Scenario 1']
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)
        ax = plt.subplot(111)
        ax.bar(1-0.15, self.TtCost_eachSc()[1], width=0.15, color='darkorange', align='center',
hatch="\\", edgecolor="r" )
        ax.text(1-0.15-0.075, self.TtCost_eachSc()[1]+30000,
str(self.TtCost_eachSc()[1]),color='k')

        ax.bar(1, self.TtPrCost_eachSc()[1], width=0.15, color='lightgray', align='center',
hatch="*", edgecolor="g")
        ax.text(1-0.075, self.TtPrCost_eachSc()[1]+30000,
str(self.TtPrCost_eachSc()[1]),color='k')

        ax.bar(1+0.15, self.TtTransCost_eachSc()[1], width=0.15, color='c', align='center',
hatch="/", edgecolor="greenyellow")
        ax.text(1+0.15-0.075, self.TtTransCost_eachSc()[1]+270000,
str(self.TtTransCost_eachSc()[1]),color='k')

        ax.bar(1+0.3, self.TtTardyCost_eachSc()[1], width=0.15, color='aquamarine',
align='center', hatch=".", edgecolor="b")
        ax.text(1+0.3-0.075, self.TtTardyCost_eachSc()[1]+110000,
str(self.TtTardyCost_eachSc()[1]),color='k')

        ax.bar(1+0.45, self.TtRemainProd_eachSc()[1], width=0.15, color='thistle',
align='center', hatch="o", edgecolor="m")
        ax.text(1+0.45-0.075, self.TtRemainProd_eachSc()[1]+30000,
str(self.TtRemainProd_eachSc()[1]),color='k')

        ax.bar(1+0.6, self.TtRemainTrans_eachSc()[1], width=0.15, color='none', align='center',
edgecolor="k")
```

```
        ax.text(1+0.6-0.075, self.TtRemainTrans_eachSc()[1]+50,
str(self.TtRemainTrans_eachSc()[1]),color='k')

        plt.title('Total Cost($) of the Case with Single Scenario using Scenario 1')
        #plt.xticks(SC, ScName)

        legend = plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.25), ncol=3, markerscale = 3000)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtCostAllScWeighted.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpCostGraph_singleSc_Sc2(self):
        name = ['Total Cost','Production Cost','Transportation Cost','Delay Cost','Remaining Qty
Production Cost', 'Remaining Qty Transportation Cost']
        ScName = ['Single Scenario with Scenario 2']
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)
        ax = plt.subplot(111)
        ax.bar(1-0.15, self.TtCost_eachSc()[2], width=0.15, color='darkorange', align='center',
hatch="\\", edgecolor="r" )
        ax.text(1-0.15-0.075, self.TtCost_eachSc()[2]+30000,
str(self.TtCost_eachSc()[2]),color='k')

        ax.bar(1, self.TtPrCost_eachSc()[2], width=0.15, color='lightgray', align='center',
hatch="*", edgecolor="g")
        ax.text(1-0.075, self.TtPrCost_eachSc()[2]+30000,
str(self.TtPrCost_eachSc()[2]),color='k')

        ax.bar(1+0.15, self.TtTransCost_eachSc()[2], width=0.15, color='c', align='center',
hatch="/", edgecolor="greenyellow")
        ax.text(1+0.15-0.075, self.TtTransCost_eachSc()[2]+270000,
str(self.TtTransCost_eachSc()[2]),color='k')

        ax.bar(1+0.3, self.TtTardyCost_eachSc()[2], width=0.15, color='aquamarine',
align='center', hatch=".", edgecolor="b")
        ax.text(1+0.3-0.075, self.TtTardyCost_eachSc()[2]+110000,
str(self.TtTardyCost_eachSc()[2]),color='k')

        ax.bar(1+0.45, self.TtRemainProd_eachSc()[2], width=0.15, color='thistle',
align='center', hatch="o", edgecolor="m")
        ax.text(1+0.45-0.075, self.TtRemainProd_eachSc()[2]+30000,
str(self.TtRemainProd_eachSc()[2]),color='k')

        ax.bar(1+0.6, self.TtRemainTrans_eachSc()[2], width=0.15, color='none', align='center',
edgecolor="k")
        ax.text(1+0.6-0.075, self.TtRemainTrans_eachSc()[2]+50,
str(self.TtRemainTrans_eachSc()[2]),color='k')

        plt.title('Total Cost($) of the Case with Single Scenario using Scenario 2')
        #plt.xticks(SC, ScName)

        legend = plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.25), ncol=3, markerscale = 3000)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtCostAllScWeighted.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpCostGraphHandling(self):
        name = ['Total Cost without Handling','Total Cost with Handling']
        ScName = ['SP Model with 4 Scenarios', 'Single Scenario with SC 1','Single Scenario with
SC 2', 'Single Scenario with SC 3', 'Single Scenario with SC 4']
        SC = np.array([0, 1.5, 3.0, 4.5, 6.0])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.25)
        ax = plt.subplot(111)
        ax.set_ylim(3500000,4500000)
        ax.bar(SC-0.15, self.TtCost_eachSc_woHandling(), width=0.15, color='aquamarine',
align='center', edgecolor="b" )
```

```
        for i in range(0,5):
            ax.text(SC[i]-0.15-0.25, self.TtCost_eachSc_woHandling()[i]+30000,
str(self.TtCost_eachSc_woHandling()[i]),color='k')

        ax.bar(SC+0.15+0.05, self.TtCost_eachSc_withHandling(), width=0.15, color='thistle',
align='center', hatch="*", edgecolor="m")
        for i in range(0,5):
            ax.text(SC[i], self.TtCost_eachSc_withHandling()[i]+55000,
str(self.TtCost_eachSc_withHandling()[i]),color='k')

        plt.title('Total Costs($) with the Handling Cost and without the Handling Cost')
        plt.xticks(SC, ScName)

        legend = plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.25), ncol=2, markerscale = 3000)
        plt.show()
        with PdfPages('TtCostHandlingScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpTtCostGraph(self):
        name = ['Total Cost']
        ScName = ['Scenario 1','Scenario 2', 'Scenario 3', 'Scenario 4']
        SC = np.array([1.0,2.0,3.0,4.0])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.2)
        ax = plt.subplot(111)
        ax.bar(SC, self.TtCost_eachSc(), width=0.15, color='r', align='center')
        A = self.TtCost_eachSc()[0]
        for i in range(0,4):
            ax.text(SC[i]-0.075, self.TtCost_eachSc()[i]+10,
str(self.TtCost_eachSc()[i]),color='r')
            if A > self.TtCost_eachSc()[i]:
                A = self.TtCost_eachSc()[i]
        plt.title('Total Costs at Various Scenarios')
        plt.xlabel('SCENARIO')
        plt.xticks(SC, ScName)
        plt.ylabel('TOTAL COST ($)')
        plt.ylim(bottom = round(9*A/10,3))
        plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.2), ncol=1)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtCostScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpTtProdGraph(self):
        name = ['Total Production Cost']
        ScName = ['Scenario 1','Scenario 2', 'Scenario 3', 'Scenario 4']
        SC = np.array([1.0,2.0,3.0,4.0])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.2)
        ax = plt.subplot(111)
        ax.bar(SC, self.TtPrCost_eachSc(), width=0.15, color='g', align='center')
        A = self.TtPrCost_eachSc()[0]
        for i in range(0,4):
            ax.text(SC[i]-0.075, self.TtPrCost_eachSc()[i]+10,
str(self.TtPrCost_eachSc()[i]),color='g')
            if A > self.TtPrCost_eachSc()[i]:
                A = self.TtPrCost_eachSc()[i]
        plt.title('Total Production Cost at Various Scenarios')
        plt.xlabel('SCENARIO')
        plt.xticks(SC, ScName)
        plt.ylabel('TOTAL PRODUCTION COST ($)')
        plt.ylim(bottom = round(9*A/10,3))
        plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.2), ncol=1)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtProdCostScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()
```

```
    def SpTtTransGraph(self):
        name = ['Total Transportation Cost']
        ScName = ['Scenario 1','Scenario 2', 'Scenario 3', 'Scenario 4']
        SC = np.array([1.0,2.0,3.0,4.0])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.2)
        ax = plt.subplot(111)
        ax.bar(SC, self.TtTransCost_eachSc(), width=0.15, color='c', align='center')
        A = self.TtTransCost_eachSc()[0]
        for i in range(0,4):
            ax.text(SC[i]-0.075, self.TtTransCost_eachSc()[i]+10,
str(self.TtTransCost_eachSc()[i]),color='c')
            if A > self.TtTransCost_eachSc()[i]:
                A = self.TtTransCost_eachSc()[i]
        plt.title('Total Transportation Cost at Various Scenarios')
        plt.xlabel('SCENARIO')
        plt.xticks(SC, ScName)
        plt.ylabel('TOTAL TRANSPORTATION COST ($)')
        plt.ylim(bottom = round(9*A/10,3))
        plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.2), ncol=1)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtTransCostScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

    def SpTtTardyGraph(self):
        name = ['Total Tardy Cost']
        ScName = ['Scenario 1','Scenario 2', 'Scenario 3', 'Scenario 4']
        SC = np.array([1.0,2.0,3.0,4.0])
        fig = plt.figure()
        fig.subplots_adjust(bottom=0.2)
        ax = plt.subplot(111)
        ax.bar(SC, self.TtTardyCost_eachSc(), width=0.15, color='b', align='center')
        A = self.TtTardyCost_eachSc()[0]
        for i in range(0,4):
            ax.text(SC[i]-0.075, self.TtTardyCost_eachSc()[i]+10,
str(self.TtTardyCost_eachSc()[i]),color='b')
            if A > self.TtTardyCost_eachSc()[i]:
                A = self.TtTardyCost_eachSc()[i]
        plt.title('Total Tardy Cost at Various Scenarios')
        plt.xlabel('SCENARIO')
        plt.xticks(SC, ScName)
        plt.ylabel('TOTAL TARDY COST ($)')
        plt.ylim(bottom = round(9*A/10,3))
        plt.legend(name,loc=8, bbox_to_anchor=(0.5, -0.2), ncol=1)
        #plt.grid(True)
        plt.show()
        with PdfPages('TtTardyCostScPlot.pdf') as pdf:
            pdf.savefig(fig)
        plt.close()

#Pareto(20).grPareto_all()
#Pareto(20).grPareto_average()

SpScenarios(1).SpCostGraphHandling()
#SpScenarios(1).SpCostGraph()
#SpScenarios(1).SpCostGraph_allScWeig()
#SpScenarios(1).SpCostGraph_singleSc_Sc1()
#SpScenarios(1).SpCostGraph_singleSc_Sc2()

###############
#SpScenarios(1).SpCostGraph()
#a = Pareto(10).lstTtCost()
#b = Pareto(10).lstTtDelay()
#print('Total Cost ',a)
#print('Total Delay ',b)
 #print(Pareto(4).lst1TtDelay())
#print(Pareto(1).lst1TtCost())
#SpScenarios(1).SpTtCostGraph()
#SpScenarios(1).SpTtProdGraph()
```

```
#SpScenarios(1).SpTtTransGraph()
#SpScenarios(1).SpTtTardyGraph()
#print(SpScenarios(1).TtRemainProd_eachSc())
```